ATOMS IN ACTION

ATOMS IN ACTION

THE WORLD OF CREATIVE PHYSICS

GEORGE RUSSELL HARRISON

Third Edition

WILLIAM MORROW & COMPANY

NEW YORK MCMXLIX

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First Published, September, 1939
Second Printing, September, 1939
Third Printing, October, 1939
Fourth Printing, March, 1941
Revised Edition, September, 1941
Second Printing, October, 1944
Third Edition, August, 1949

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F. K. H.

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Preface to Third Edition

ATOMS IN ACTION is not a technical book. There is not a single equation or formula anywhere in its pages. It was written for every imaginative person who has ever dialed a telephone number, snapped a camera shutter, played a phonograph record, removed an ice cube from a refrigerator, watched an airplane droning above the clouds, had a tooth X-rayed, or bought an Easter lily. If you have done any of these things it was written for you. "But what have all these things to do with atoms?" is a reasonable question. The answer to that question is contained in the book—in fact, it is the book.

These pages are concerned with atoms because every physical thing we live with is made of atoms. By putting these atoms into new and exciting action physicists have been changing our world, affecting our daily lives, and exerting a primary influence on our health, comfort, security, and happiness. Now, with the successful release of power from the atom, it is more important than ever that the intelligent citizen understand the new forces which science has made available to mankind.

The statement is sometimes made that it is becoming increasingly difficult to put the advances of modern science into

a series of clear mental pictures. The electron, it has been said, is definitely outside the possibilities of pictorial imagination. Worry about this shows a complete misconception of what electrons are good for. Certainly it is a waste of time to try to visualize what an electron looks like when an electron is, by its very nature, unseeable. To the general reader the important fact about an electron is that it can be used to his advantage in lighting his home, telephoning to his partner in Bermuda, or setting his son's broken arm; and these things *can* be put into a series of clear mental pictures.

During the decade that has elapsed since the first edition of this book was prepared, more has happened in physical science than occurred in any previous generation. In 1939 the richest man in the world could have obtained no more than 86 chemical elements; in 1949, 96 elements can be obtained in bottles for anyone to see.

Two chapters not in the original book have been added to this third edition, and the entire volume has been revised and brought up to date. In the new chapters will be found discussion of some of the consequences on human welfare of the work of the scientist in so rapidly shrinking our world and expanding our universe. Never in previous time has this process gone on so rapidly as in the ten years that have elapsed since this book appeared in its original form.

G. R. H.

Cambridge, Massachusetts
January, 1949

ATOMS IN ACTION

I

THE TAMING OF ENERGY

Bright-flaming, heat-full fire, the source of motion.

DU BARTAS

WHETHER yesterday was sunny or cloudy, a June day or a day in December, enough energy fell on the earth during that twenty-four hours to serve humanity for several centuries—enough to keep the world's furnaces roasting and its refrigerators icy, to spin its wheels and refine its ores, and to fill for several hundred years every other present need for power. The wheels of civilization are kept turning by energy; and all this energy, whether we draw it from a gallon of gasoline, a ton of coal, a pound of butter, or an atom of uranium, has come to us from the sun.

So long as the sun keeps shining we appear to have little cause to worry about running out of energy, and the best evidence indicates that our powerhouse in the heavens will still be glowing brilliantly a billion years from now. Unfortunately, however, most of the energy we are now using came from the sun in ages past, and we are drawing heavily on the earth's savings account of coal and oil instead of using our current energy income. Even though the sun sends us two hundred thousand times as much power as we use, most of this slips through our fingers, merely because we have not yet learned how to convert sunlight efficiently into those forms of energy which are useful for civilized living.

Select on a map any convenient desert, and look at an area twenty miles square—an area which would about cover the sprawling environs of a great city. Year after year enough sunlight is lavished on this small sandy waste to satisfy perpetually the power needs of the entire population of the United States at the present rate of power consumption. In fact, grimy miners digging six thousand tons of coal from the gloomy depths of the earth obtain only an amount of energy equivalent to that swallowed on a sunny day by a single square mile of land or sea.

Almost every material problem of living turns out in the last analysis to be a problem of the control of energy. The householder, when he has paid his bills for fuel and electricity, is likely to consider that he has taken care of his energy requirements for the month, yet each bill from the grocer or the milliner is quite as truly a bill for energy. We do not buy a basket of strawberries for the carbon, oxygen, and nitrogen atoms they contain, but for the energy stored by these atoms when they join together in molecules to form sugars, starches, flavors, and vitamins. That part of the cost of a lady's hat which does not represent business acumen on the part of the milliner is for stored and directed energy—the atoms of matter of which the hat is composed are permanent, and will still exist when the hat has been discarded and burned. Only energy and knowledge of how to apply it are needed to re-create a hat from its smoke and ashes!

Even such materials as gold, silver, and copper represent true wealth only as they represent the energy required to find, collect, and purify these metals. Our supply of matter on earth is not changing appreciably, for although a little hydrogen and helium leak off from the top of the atmosphere, far more matter than we lose in this way is brought to the

earth by meteorites. Iron may rust or be scattered, but it cannot be lost so long as sufficient energy remains to reconcentrate and re-refine it. Many a mine long abandoned as worthless has brought in a fortune when cheaper power or a more efficient concentrating process has made worth while the recovery of further metal from its scrap-heap. Only energy is needed to gather as much of every material as we may need from the air, the land, or the sea.

Energy is wealth, and in the case of apprenticed sunlight, wealth of a particularly desirable kind, for it is freshly created and does not involve robbing the poor, taxing the rich, or despoiling the earth of materials which may be needed by our descendants as much as by ourselves. Yet this energy is free—to him who can discover how to capture and control it.

2

THE SCIENTIST who is most concerned with the investigation and control of energy is the physicist. In his researches on energy the physicist works very closely with the chemist, who is interested primarily in matter. Matter and energy are always closely related; and physics and chemistry, originally a single science called natural philosophy, can never be separated completely, for they are the twin sciences which deal with the fundamental structure of our physical universe.

The chemist gathers the minerals and fibers and oils which he finds in nature, reduces them to the elementary atoms of which they are composed, and then causes these atoms to recombine into thousands of new kinds of molecules, thus forming new perfumes and dyes, new flavors and fabrics and drugs.

The physicist, however, takes apart the very atoms themselves, sending through wires the electrons which he thus collects, and operating with them his telephones and X-ray tubes and television outfits. Or he may induce the atoms to emit light rays of strange new colors, rays which he bends with lenses designed to enable him to discern objects which are too dark or small or transparent otherwise to be seen.

As the physicist has gradually learned to control the grosser forms of energy such as heat and sound, he has been led to probe deeper and deeper into nature in studying the behavior of energy in its finer and more subtle forms, such as light and electricity and magnetism. He has now succeeded in penetrating down through the atom into its tiny nucleus or core, and one of his principal interests at the moment (though by no means the only one, nor necessarily the most important one) is to take sample atom cores apart to see what they are made of and how they are put together. The atom is being taken to pieces quite literally, for when one of the modern "atom-smashing" devices is put into operation the atomic debris comes flying out like dirt from a gopher hole in which a very industrious puppy is scratching. Recently the large-scale release of energy from atoms has stopped man's most violent war dead in its tracks.

The scientist who appears preoccupied with the center of the atom is burrowing after the key to the structure of matter and energy, not only because he expects to tap the energy in the atom, but because he knows that before nature can be controlled she must be understood. The physicist who is engaged in "pure" or fundamental research is attempting to understand nature. The applied physicist is attempting to control nature. The two kinds of investigators try to keep in close collaboration, but physics is a vast science which ranges

from such theoretical subjects as Relativity to such practical applications as the phonograph, as the interests of its workers have ranged from those of Einstein to those of Edison.

As the examples given in the following chapters will attest, "atom smashing" (using the term broadly to cover fundamental research into the structure of matter and energy) pays astonishing dividends—not a mere five per cent, nor one hundred per cent, but hundreds of times the investment. This is not fanciful romanticism, but stark bookkeeping which realistic corporations, headed by typical American business men, have many times demonstrated to their stockholders.

The scientist, like the artist, creates something new merely by rearrangement of the old. An industry that gets its profits from digging coal or pumping oil or felling timber is constantly depleting its resources. An industry that rests on a physical discovery gets its profits through fresh creation.

Since wealth consists ultimately of the control of matter and energy, the wealth level of mankind slowly rises as science learns to capture a constantly growing fraction of the energy that is available and turn it more effectively to useful ends. A factory worker in the United States is paid several times as much in real wages as his predecessor received a generation ago. While management and labor may justly claim credit for this improvement, it was made possible only by utilizing technological achievements resting on scientific discoveries, which made the labor of each worker more productive. For the wages he received for one hour of labor in the middle 1930's a factory worker in Italy could buy a certain amount of food, a similar worker in Great Britain could buy twice as much, but a worker in the United States could buy four times as much. Economists agree that technological development and scientific discovery have been responsible

for this higher level of plenty in the United States. Science is a great agency for social betterment, for the victories over nature which result from its application make possible increased wages and profits and reduced prices at the same time.

Experience has shown no better way of eliminating poverty than by well-directed "atom smashing." Poverty can best be abolished by replacing it with wealth; and the systematic investigation of matter and energy without regard to immediate practical ends has turned out to be the most direct road to social riches. In the long run digging for truth has always proved not only more interesting, but more profitable, than digging for gold. If urged on by the love of digging, one digs deeper than if searching for some particular nugget. Practicality is inevitably short-sighted, and is self-handicapped by the fact that it is looking so hard for some single objective that it may miss much that nature presents to one who is purposefully digging for whatever may turn up.

Each dweller in the United States is now served, on the average, by energy equivalent to that which could be provided by thirty slaves such as sweated at the command of an ancient Egyptian king. In making this much energy available, science has contributed only a small fraction of what it can contribute. Human beings can be made at least twenty thousand times as wealthy as they are today; but only the fundamental investigation of nature, such as is involved in "atom smashing," will show how.

[3

ENERGY CAN NEITHER BE CREATED NOR DESTROYED (except as it can be changed into matter under certain extreme condi-

tions, and produced from matter as in the fission of uranium), but it can appear in any of a dozen or more forms. If the physicist succeeds in backing a bit of energy into a corner, so to speak, he usually expects it to disappear like a witch in a fairy tale, and to reappear in an entirely different form. By careful study of many typical situations he has learned where to lie in wait for the reappearance of the energy so that he can pounce on it in its new guise, or, if it stay hidden, ferret out its place of concealment. All of our most useful machines, such as electric motors and kitchen ranges and cameras, are merely clever devices for beguiling energy of one form into changing itself into another form. By touching a match to a gallon of gasoline we can cause the chemical energy which the gasoline contains to be transformed into thermal energy; but if instead we use a spark plug in an automobile cylinder, much of the thermal energy, when it appears, will find itself harnessed to perform mechanical work.

The most useful forms of energy for practical purposes are those we call heat, sound, and light, and the mechanical, electrical, magnetic, chemical, and gravitational forms. When we have learned how to convert energy from any one of these forms directly into any other at will, without letting much energy escape in the process, the millennium will have arrived so far as the cost of living is concerned.

If, for example, we knew how to convert electrical energy directly into light, the problem of "cold light" would be solved. At present we must use indirect means, as in the incandescent lamp, where electrical energy is forced to heat a tungsten filament and thus is turned into heat energy. When heat has set the filament glowing some of its energy is transformed into useful light as a by-product, but nine-tenths of

the energy is wasted as invisible radiation, boosting our electric light bills to ten times what they should be.

An example of the many useful applications which often result from the discovery of a new way of transforming one form of energy into another is given by the piezo-electric crystal. The brothers Pierre and Paul Curie found in 1880 that sensitive crystals of certain types, such as quartz and Rochelle salt, shrink and swell when given electric shocks. Thus was discovered a new method of changing electrical energy into mechanical energy. The crystals were found also to generate electric charges on their surfaces when squeezed or stretched, so they could be used to convert mechanical energy back into the electrical form as well. The Curie brothers were academic physicists, interested chiefly in digging out facts (Pierre, with his wife Marie, later discovered radium), so they made no use of their discovery. It lay unapplied until 1917, when, during World War I, another physicist decided that crystals might be useful for detecting the sound waves given out by submarines. His work was so successful that it suggested further fields for investigation, and later we shall find piezo-electric crystals being used for such diverse purposes as keeping radio broadcasting stations tuned to the proper frequency, serving as microphones for changing sound waves into electrical waves, and forming wave-filters which keep separate more than two hundred telephone conversations passing simultaneously over the same pair of wires. These accomplished crystals also make excellent phonograph pickups, can be used as telephone transmitters and receivers, and operate the most accurate clocks in the world, which tick 100,000 times a second. Again, by tickling such crystals electrically at high frequency they can be made to emit supersounds, which

are of value for cracking crude oil to increase its yield of gasoline, for precipitating smoke, for detecting icebergs or other obstructions at sea, and even for speeding up the pickling of cucumbers!

The delay of thirty-seven years in putting the piezo-electric crystal to work occurred because good methods of applying rapid electric shocks to the crystal were not available until the electronic vacuum tube was invented, which in turn waited on the discovery of the electron. Thus the application of one important discovery is often forced to await the birth of another.

Most of the physical developments which are discussed in this book involve special transformations of energy from one form to another—as in telephony, where sound vibrations are changed into electrical vibrations, carried through space on waves or over wires, and then changed back into sound vibrations; or in television, where the same is done for visual images. But fundamental to all such processes is the transportation and storage of energy in bulk.

¶ 4

TRANSPORTING ENERGY FROM PLACE TO PLACE keeps millions of men busy. Most energy is transported in one of three ways: in coal carried by ships or freight cars; in oil carried by ships, tank cars, or pumped through pipe lines; or sent over wires as electrical power. More than half our energy is carried in coal. Electrical power is more convenient to use than any other kind, but even when energy is ultimately to be delivered in electrical form it is cheapest at present to carry it locked in coal or oil for as much of its journey as possible.

In the United States there are more than 120,000 miles of pipes through which black oil flows, sometimes for more than a thousand miles on a single journey; 75,000 additional miles of pipe carry natural gas for fuel, and together these buried pipe lines form a transportation system three-quarters as long as all the railroad tracks of the country. About half as much energy as is carried by oil and gas flows through wires, carried by electric currents consisting of countless electrons sent swinging from one copper atom to the next.

To carry energy to its user costs much more than to dig it out of the ground as coal or to scoop it up with turbine blades from a waterfall. Though a ton of coal costs less than eight dollars at the mine, delivered to the ultimate user it may cost three times as much. Electrical energy delivered in the home now costs on the average five and a half cents a kilowatt hour, more than ten times its cost to produce in wholesale lots at a steam plant near a coal mine. There is great need for development of cheaper electrical methods of transmitting power. Standard engineering methods are beginning to be found insufficient—new methods must be provided by applying physics anew.

At present electric power cannot be piped economically farther than a few hundred miles unless expensive special equipment is used; only when a tremendous load of power can be sold is it economical to provide this equipment. The electrical engineer delivering his kilowatts is in much the situation of a small boy carrying home sugar from the grocery store in a paper sack with a hole in its bottom which lets the sugar trickle slowly away. Since the engineer cannot now afford to plug the hole, only those persons can afford to buy electrical sugar whose homes are within a few hundred miles of an electrical power store.

It has long been known that the most efficient way to send power over wires of a given size is to keep the flow of electric current as low as possible, and make the voltage, or electrical pressure of the line, as great as possible. Engineers have a working rule which says that a power line should be operated at such a high voltage that 1000 volts is provided for each mile the power is carried. Since 350,000 volts is about the economical upper limit of voltage practical on present power lines, this sets a 350-mile limit.

In 1948 the longest power line stretched 270 miles from Boulder Dam to Los Angeles. To carry energy from such great water-power developments as Tennessee Valley to the large cities where power is most needed, methods of using higher voltages must be provided. But raising the voltage of a standard power line above 350,000 volts may cause the bottom to drop out of the electrical sugar bag—the air, the line, and the insulators refuse to co-operate longer in keeping the electrical flow intact.

Long-distance transmission lines now operate with alternating current, briefly written A.C. Electricity is first pushed into one wire of the line and pulled from the other, and then the push and pull are reversed. Pushes and pulls are usually alternated 120 times in a second, giving 60-cycle A.C. Power can also be transmitted with direct current (D.C.) by pumping electrons continuously into one wire and out of the other, and it is known that with such D.C. transmission much less electricity leaks from a line than with A.C. Short lines operating at more than a million volts D.C. have been used experimentally to carry power. However, the transformers which give the most convenient means of stepping electricity up from a low voltage to a high voltage, or stepping it down again, operate only with alternating current. For safety, power

must be generated and used at low voltages; yet for economy it must be sent over a long line at high voltage. This combination of necessities sets a pretty dilemma.

Here the electronic vacuum tube, to which a later chapter is devoted, enters the picture; and with its aid the problem may well be solved. With tubes of one type direct current can be changed to alternating current at any voltage. By using tubes of a second type alternating current can be changed to direct. Such tubes should make it possible to generate alternating current power, step this up to high voltage with transformers, change the power to D.C. with a vacuum tube and send it over the long-distance power line, at the far end change it back to A.C. with another vacuum tube, and then step it down with a transformer to the desired voltage for use. This process of sidestepping nature's obstacles, which might be described in football terms as a double lateral pass with a forward pass between, sounds complex, but actually it is simple once the vacuum tubes have been put into reliable working order. A trial installation of this sort was kept in satisfactory operation by the General Electric Company in Schenectady for several years.

An entirely different attack on the problem of high-voltage D.C. power transmission has been suggested by the work of an atom-smashing physicist, Dr. Robert J. Van de Graaff, and his collaborators. They were interested, not so much in developing a new means of transmitting power, as in perfecting a high-voltage machine which would generate 5,000,000 volts with which to hurl electrical bullets against the cores of atoms which were to be smashed. In Van de Graaff's generator, electrons are sprayed against wide rubber belts. To these belts the electrons stick, and by them are carried up into a large metal sphere, which they gradually charge with electricity. The

sphere is carefully insulated from the ground by a tall supporting column, and so smooth and round is this sphere that electricity can leak into the air from it but slowly. If electrons are pumped indefinitely into the sphere its electrical pressure rises until finally a voltage is reached which the air can resist no longer, and a great flash of artificial lightning jumps between the sphere and any near-by object connected to the ground. With such a generator several million volts might be applied directly to a power line, no transformers would be needed at the beginning of the line, and extremely weak direct currents would suffice to transmit large amounts of power with little loss.

Scientists have envisaged long D.C. lines consisting of a pipe, buried in the earth with a wire stretched down its center, carrying power from great hydraulic turbo-generators, or from steam plants located near coal mines, to any city in the country. The pipe might be filled with carbon tetrachloride vapor, or with the Freon vapor used in refrigerators, to reduce leakage of electricity between the wire and the pipe. It has even been suggested that the pipe might be evacuated over its whole length of more than a thousand miles, for electricity cannot leak across a well-evacuated space. To obtain a suitable vacuum thousands of high-speed pumps would have to be kept sucking on the pipe like piglets on a myriad-breasted mother pig. At present such a project is perhaps visionary, but it illustrates how the practicability of an engineering scheme may hinge on new developments of physics—in this case, on a high-voltage generator and a more efficient vacuum pump.

Must wires always be used to carry electric power from place to place, or could rays be used instead? Dreamers have long talked of powerful rays which could be focused on dis-

tant machinery to which energy was thus supplied. Keeping airplanes aloft without fuel is a favorite application. At present no rays energetic enough for this purpose and at the same time available in quantity are known to scientists. Radio waves and light waves are more suited to such comparatively dainty tasks as carrying messages than to feeding engines with power. Machinery can be operated with the energy contained in rays of sunlight, to be sure, but the power these carry is insufficiently concentrated to be worth using at present, even when available. Rays of more concentrated types have either insufficient penetrating power to travel far through the air, or are uncontrollable, or are available only in very small quantities. Energy can be most readily controlled by giving it matter to cling to when it is to be stored, concentrated, or carried from place to place with little loss. Atomic fuel, of the sort developed during World War II and released first in 1945, may well turn out to solve many problems of energy storage and transportation.

❡ 5

TO STORE ENERGY FOR FUTURE USE is much more difficult than to release energy already stored in matter. When fuel is burned, the chemical energy stored in it is released as heat energy; but the reverse process—unburning a gallon of gasoline or a cord of wood—is very slow and difficult. Nature unburns wood when she uses sunlight in plants to release carbon atoms from the carbon dioxide molecules which the leaf has picked up, wafted through the air from some long-forgotten fire. Man has not yet learned to imitate nature in this regard, though he is beginning to get some clues as to how it is done.

One can store energy mechanically, as by winding a clock or bending a bow; electrically, as by charging a condenser; gravitationally, as by pumping water into a high reservoir; thermally, as in a hot water bottle; chemically, as by charging a storage battery or growing a tree; and in many other ways. All involve associating energy with matter.

In comparing storage processes a most important question is, How much energy can be packed into each pound of matter? We can get an idea of the energy-holding capacity of matter by seeing how much energy can be released from a pound of each of a number of fuels; this energy can readily be evaluated in terms of how long a pound of the fuel would keep a 60-watt incandescent lamp burning if all its energy were converted into electric power. Thus, a pound of wood would keep the lamp alight for about 200 hours, a pound of coal for twice as long, a pound of gasoline for 900 hours. Hydrogen is one of the best chemical energy-storing substances obtainable, for in a pound of this gas is stored enough energy to keep the lamp bright for nearly 2700 hours. Atomic energy storage is even better, for a pound of atoms of any kind whatever contains enough energy to keep the lamp burning for millions of years. Scientists do not yet know how to release all of this energy, however, though they have recently tapped a small portion of it in a few kinds of atoms, as in the atomic bomb and the uranium pile.

Any method of producing ordinary fuels is a method of storing energy in chemical form; and chemical storage, in which the energy is tucked between atoms when these are grouped together to form molecules, appears to be the best of any practical method now available to store energy with little weight. Even fuels are heavier energy-storage reservoirs

than we would like, however; witness the concern of the aviator whose two tons of gasoline must carry him across the Atlantic Ocean.

Any youth who wishes to win fame and fortune through scientific discovery, but who cannot think of anything which needs discovering, would do well to turn his attention to the problem of storing energy lightly. If he could invent a device into which electrical energy could be fed, which would store this energy chemically and later release it again as electrical energy, his fortune might be made—if the device was light enough. Such a device is, of course, merely a storage battery; but all present efficient storage batteries are far too heavy to be used for anything but odd jobs such as starting automobiles. One pound of ordinary lead storage battery, when fully charged, holds less than one-twentieth as much energy as is contained in a pound of gasoline.

If a storage battery weighing less than one-tenth as much as present batteries were to become available, the electric automobile would probably supersede the gasoline motor car almost immediately. What magic does the heavy lead atom, now used for almost all storage of electrical energy, possess which enables it to store energy and give this out again at the will of the user, which is not possessed by, say, the lithium or the beryllium atoms, weighing one-thirtieth as much? There seems to be no reason for supposing that a light storage battery cannot be invented, except that many people have tried doing this, and no one has yet succeeded. Such arguments have, of course, never deterred resourceful men. To invent a light battery, the old method was to start by trying thousands of different light materials; the new method is carefully to study nature and find how she packs energy into atoms and molecules.

When any scientist first learns that as much as one horse-power is falling on each square yard of fully sunlit earth's surface, he is likely to have an almost irresistible urge to do something about collecting this energy for some worth-while purpose before it reaches its inevitable destiny of warming up the earth. How pleasant it would be to store up our winter supply of power for house-heating and cooking merely by sunning rows of little black boxes on the roof during the summer, knowing that not only were they helping the keep the house cool, but were soaking up sunlight and imprisoning this to await use six months later! All that is necessary to accomplish this miracle is to find the black boxes—to invent some efficient means of storing the energy of sunlight. If we could convert sunlight efficiently into electrical energy, and then use this to charge storage batteries which would hold ten times as much energy per pound as those available at present, the problem would be solved. It is the main purpose of this book to show that many projects more visionary than this have already been transformed into useful reality.

Sunlight is difficult to capture efficiently because it is gentle, mild, and diffuse. Scientifically speaking, it is energy of low potential, and hence its use is inevitably wasteful except in installations built on a grand scale. Water power is stored solar energy which can be used efficiently because it has been concentrated in space, yet even with this concentration it has difficulty in competing economically with that great concentration of energy in time known as coal.

Some day the problem of storing solar energy efficiently will no doubt be solved. In the meantime, farmers store solar energy by the time-honored methods of nature; and agriculture is found to be a field of human endeavor well worth the attention of the physicist.

II

WHEN PHYSICS GOES FARMING

The desert shall rejoice, and blossom as the rose.

Isaiah xxxv, 1

FROM the standpoint of the physicist, a farm is a packaging establishment where energy from the sun is bottled up in the molecules of matter and stored for future use. From the standpoint of the chemist, a farm is a factory where energy from the sun is utilized to change cheap simple molecules into valuable complex molecules. That farms flourished long before chemists or physicists is beside the point; chemists have in recent years had much to contribute to the development of new agricultural methods, and that farmers are being aided by physicists is equally true, though not so obvious.

Agriculture, the world's greatest industry, is still in the era of its development which corresponds to that of the sailing ships of a hundred years ago. The continued existence of two billion human beings depends on what the land produces, but farming still remains in most instances a back-breaking, discouraging process of slim and uncertain profits. An annual return of eighty dollars from an acre of land chosen at random is still considered princely in some regions; thirty dollars is an average gross return. After long hours of labor, the farmer and his family may, if their sprouting seeds are not eaten by birds and insects, washed away by floods, blown

away by winds, or withered by drouths, produce a crop for which the demand has vanished because of overproduction. The annual cash income of a farmer in the United States is usually considerably less, barring subsidies, than that of an unskilled laborer who knows only how to dig ditches.

Perhaps the art of agriculture has not felt the need of scientific methods more acutely because it has always had something of the appearance of a free lunch. The passing motorist picking the farmer's apples at the roadside considers himself to be merely sharing in the gifts of Providence—seeds cost nothing, since any apple core in the street is filled with them; plant a seed, let the heavens water it and the blessed sun shine upon it, and pick your apples when they ripen! The newly embarked agriculturist is likely to feel this same emotional response to the call of the soil. Twenty years later, if he is still farming, his response has usually been considerably modified.

The cheapest way to accomplish some end often is not the most economical. The winds blow free across the seas, but it is cheaper to spend $10,000 on oil to send a liner from New York to Liverpool than it is to fit the same vessel out with $2000 worth of sails and accept the freedom of the winds. The original farmer merely picked his crops where he found them growing wild, as the first boatman floated on his log wherever the current carried it. Then the farmer scratched his land and sowed his seed, and the boatman learned to paddle with a stick. When the boatman invented a sail, the farmer matched him with an irrigation ditch. Then the sailor called in the scientist to help him; or rather, he found the apparatus produced by science forced upon him by economic necessity. The farmer with ambition feels that he too has become very scientific during the last thirty years. However, his

experiments with scientific farming appear as yet but as a chugging paddle-wheeled ferry when compared to the steamboat of possibility.

Plant growth has four basic needs: light, air, water, and a comparatively small supply of a few chemical elements. The plant abstracts from the air the materials which it needs most to build its structure. Since the chemical reactions within its cells can take place only in solution, water must be stored in them; and its pressure in the cells helps give rigidity to the plant structure. Light furnishes the energy with which the plant abstracts carbon atoms from carbon dioxide molecules taken from the air. With these carbon atoms and hydrogen and oxygen atoms from water and air, the plant builds starches and sugars which carry to man much of the chemical energy which he uses in his body. In addition to its edible components, the plant also builds up cellulose materials which man burns, saws, spins and otherwise shapes to his advantage.

All this sounds very chemical, but once the proper fertilizing ingredients have been added to the soil (if not already present) the plant carries out these chemical operations very effectively, and the chemist comes into the picture largely in connection with utilization of the crop. The great primary problems of farming, apart from fertility, involve investigating and controlling temperature, light intensity, soil mechanics, and water application and disposal, all of which are problems of physics and the technology which springs from physical science.

The full time of a few physicists is now being given to research designed to improve agriculture, but considering its importance as an energy-storing industry the field would justify the attention of many more. The agricultural income

of the United States varies between fifteen and thirty billion dollars per year. Even with less land than at present, improved methods would increase this income many fold. Increasing agricultural efficiency is not essentially different from designing telephones which will operate over greater distances —it merely requires co-operative research of a broader variety.

A basic change which would revolutionize agriculture is the provision of cheap power wherever it can be used effectively. The power is available—what is needed most is research to find improved methods of transporting power cheaply and of utilizing it economically.

If fresh ripe cherries are desired in Maine in December, there are three ways to provide them. The fruit could be brought at high speed from Australia or the Argentine or wherever else cherries are ripe in December; improvements in transportation are needed to make such hauling profitable. Or the cherries could be raised wherever cherries will grow, picked whenever they ripen, and then kept until December by some method which would preserve them unchanged for at least six months—a cherry which cannot be distinguished from a fresh cherry *is* a fresh cherry to its consumer. Or the cherries could be raised in Maine in December by treating the cherry trees in some way that would make them feel June weather about them. All three of these methods are at present in promising stages of development, and the principal requisite needed to make them economically practicable is cheaper energy. In fact, if electrical energy could be delivered to farms at the rate at which it is now sold wholesale to industrialists near large power-producing plants—a rate sometimes one-tenth what the farmer has to pay—the second and third methods would now be feasible and profitable. That rural power could be made cheaper by proper organization is em-

phasized by the fact that a large fraction of the average electric power bill is paid, not for power, but for the privilege of turning it on or off at any time.

The United States is somewhat behind the times in farm electrification even for such obvious things as water pumping, wood sawing, and the thousand other tasks that for years have added to the drudgery of farm life. When a man saws wood by hand, he is earning five cents an hour, which is what it costs on the average to have electricity do the same job. In Switzerland and Sweden a large proportion of the farms are equipped with electric power; in widely scattered parts of this country less than 20 per cent of farms are so equipped, and this in spite of the fact that the United States uses ten times as much electric power per person as the average of the rest of the world, and that its domestic and industrial power consumption is climbing steadily. On one farm of 600 acres in England only two horses are kept, while over sixty different uses are made of electricity. In Holland the windmill, that picturesque feature of the landscape which has furnished cheap power for so many years, has rapidly been displaced by electric motors which are fed power generated from coal. The number of windmills has been cut in half, and, by going to the additional expense of importing coal, the Dutch market gardeners have been set free from the vagaries of wind and weather to such an extent that they have been able to capture much of the fresh vegetable market of Great Britain once held by Italy.

¶ 2

THE USE OF ARTIFICIAL LIGHT to supplement sunlight has been found of economic advantage, both to hasten and to

retard the maturing of flowers and fruits. No present-day lamp can supplant the sun, for the sunlight falling on a square yard of garden surface costs at least three cents an hour to duplicate electrically, a figure which grows to more than $1000 per acre per day. Artificial light may profitably serve to eke out sunlight on dark days and sometimes during the night, but electrical energy cannot compete directly with solar energy until some cheaper way to produce it from solar energy than is at present available has been discovered.

Forcing lilies for Easter is an old trick, and proper artificial illumination will expedite blooming by as much as a month. Sweet peas have been made to bloom five weeks in advance of normal by means of artificial light. One type of clover, which scientists of the Boyce Thompson Institute for Plant Research in Yonkers, New York, found ordinarily required two years to come to bloom, was brought to flower in one tenth of this time under artificial light. Forcing by means of light appears more suitable than forcing by other means, as it is accompanied neither by a loss of color or fragrance in the case of flowers nor by a loss of color or flavor of fruits.

Some plants thrive on a long working day, while others respond best to a short day. Chrysanthemums, which tend to bloom too soon for the best market, can be retarded by giving them extra-long days of growing under artificial light. Plants which bloom in midsummer respond best to a long day; those which bloom in spring or autumn prefer a day of medium length; those which bloom all the year round appreciate shade occasionally when the days are long. Light judiciously applied makes flowers and fruits more brilliant and colorful. But brilliant light must be used; the dim illumination provided in the average living room is negligible compared to that which a plant gets from the sun out in the open, where the light is ordinarily a thousand times as intense.

Filtered light may be useful, as some plants are injured by the heat content of solar radiation. Only one-fifteenth of the energy in the light from the sun is of the proper colors to be used by plants; the remaining 93 per cent serves only for heating air and soil, and may burn delicate plant tissue. In the future we may see greenhouses with clear glass above, to let in as much radiation as possible, and with internal colored glass shields over certain plants to protect them from the heating rays while allowing the useful colors to pass.

That all colors of light are not equally effective in promoting plant growth may be inferred from the fact that leaves are bluish green in color. The absorption of light by chlorophyll and by both dead and living plant leaves has been carefully studied, and red has been found to be the color most vigorously absorbed and utilized.

By growing similar plants under conditions identical except as to illumination, one group of plants being under blue light, another group under red, with others bathed in infra-red and ultra-violet light respectively, it has been found that such widely differing varieties of plant life as the buckwheat and the green scum which grows in stagnant ponds respond similarly to light stimulation. Biophysicists have found that yellow light from an incandescent lamp will stimulate growth half again as fast as blue light from the same source, while a given amount of yellow light energy from a sodium vapor lamp produces more than twice as much growth as the same amount of bluish energy from a mercury arc lamp.

Pure blue light appears to retard plant growth, while ultra-violet light is definitely injurious. On the sides of high mountains, plants which in the valleys below grow luxuriantly are often found flourishing but stunted, an effect attributed to the smaller cell structure promoted by the intensity of blue and ultra-violet light at high altitudes. The edelweiss of the

Swiss Alps is a small plant, but when brought down into the valleys it grows tall and bushy. When taken indoors and illuminated with blue and ultra-violet light from special lamps, it grows dwarfed and spindly as on the mountain peaks.

A collector of tropical plants is said to have been presented, during a visit to the mountains of Central America, with a small shrub known as a dwarf milkweed, which was widespread in that region. On his return to the United States he gave it to a botanical garden specializing in sub-tropical plants and thought nothing more of it. A year later, when he visited the garden, its director told him that he would like to have his help in identifying a great vine several hundred feet long, which was climbing along a fence and threatening to encircle the entire institution. The collector could make nothing of it, and finally stated his belief that the vine belonged to an entirely new species. "That," said the garden manager, "is your dwarf milkweed." So great is the influence of physical environment on plant growth.

Most florists and hothouse vegetable growers who pride themselves on up-to-the-minute greenhouses are supporting inefficient, expensive, and archaic structures. A greenhouse is supposed to be an illuminated energy trap. Light of most of the wavelengths received from the sun penetrates glass, and once inside the greenhouse it is absorbed by plants and soil. As the temperature within the structure rises above that of the outside air, its inner contents begin to radiate heat, but the heat waves radiated from objects so cool cannot penetrate glass. Since the entrapped radiation cannot escape it must devote its energies to building up the internal temperature of the greenhouse still further.

On such valid principles of physics was the greenhouse designed, but all too seldom are these principles followed correctly. There is little point in having glass on the north side

of a greenhouse, for the north half of the sky gives only one-ninth as much radiant energy as the south half when the sun is shining, and more heat is conducted out through the glass than comes in. Scientists of the Boyce Thompson Institute in Yonkers, New York, have designed a new type of greenhouse which turns out to be cheaper to construct and to operate than the ordinary type, and far more efficient. This greenhouse contains little glass, but what glass there is is so disposed as to catch every possible ray of the sun, and to cut down losses by reflection. One-half the roof, both ends, and the back wall of the greenhouse are all of sheet metal stuffed with sawdust for heat insulation. No crack is allowed in the walls, for out of this would escape the heat which is to come not only from the sun when sunlight is available, but from electrical sources as well. The usual greenhouse designer has a custom of lapping the panes of glass like shingles, perhaps acting from a feeling that plants must have fresh air, but this process leaves tiny spaces through which heat pours from the inside of the house.

The Boyce Thompson scientists use electric light to lengthen the growing day of the plants when this is desirable, and so add as much as four hours of extra growth each day. When the temperature falls below the desired value the high-power lamps are automatically turned on and the heat from these keeps the hothouse warm. Even with expensive domestic power the cost of the four hours extra light and the entire heating was only thirty-six cents per day for a large greenhouse. In this way June is brought to the plants in January, and flowers, vegetables, and fruits can be raised profitably out of season, when they command relatively high prices.

With such extensive precautions against external weather variations it is necessary to provide artificially what before was always present as a gift from nature—gas for the plants

to breathe. In one corner of a typical Boyce Thompson greenhouse a block of solid carbon dioxide (dry ice) is buried in sawdust, to evaporate slowly and furnish the gas which to the plants means fresh air. A tiny fire of any sort, to burn the excess oxygen given off by the plants and produce the carbon dioxide they need, would do as well and would give additional heat, but would require more attention. Scientists have developed a method by which changes in the carbon dioxide content of the air as small as one part in a million can be measured by using infra-red rays and the spectroscope, thus employing light to determine how fit the air is to be breathed by plants.

Though a large greenhouse can be kept at summer temperatures fairly economically with steam heat, electric heating is more satisfactory, as it can be applied rapidly where it will do the most good, can be thermostated readily to keep any desired constant temperature, and can be used in the form of light so as to increase growth. To heat the present-day greenhouse electrically is expensive, but with proper design to conserve heat, and with the cost of power cut down, it should be profitable to control in this way the weather over vast acres of gardens near the centers of population. A tomato plant twenty-five feet high and forty feet wide, unaware that February has come to New England outside, is a profitable investment, especially if it bears twenty times the normal yield and the fruit matures in half the normal time.

3

THE PRINCIPAL PART OF ANY FARM is usually considered to be the soil. That soil is not essential is shown by the experiments which have been undertaken by a number of scientists who

have sprouted seeds on blankets of moist excelsior or sawdust dipping into trays of chemical-laden water. Twenty-fold increases in yield of various crops from strawberries to hay are reported, and though the first bloom of this gardening fad has now worn off, it still holds great potentialities. Under these conditions an acre of land becomes merely a space on the earth's surface which can be occupied, and the stoniest Vermont hillside, if it be near a large city, may become more valuable than a rich but isolated California valley. When soil is depleted and the farmer starts replenishing it with expensive chemicals, he begins to realize that the main contribution of soil is mechanical; it holds the plant upright in a given spot, keeps it from being blown or washed away, and allows water to seep slowly in thin films to its rootlets. However, the chemicals provided by nature, as well as the sunshine, air, and water, are too valuable to neglect entirely, and field crops in the open will always remain of importance.

A single grass plant has been found to grow roots at the rate of over two miles a day. One two-year-old plant was found to have a total root length of over 300 miles, though no single rootlet was over seven feet long. The soil must be like a sponge through which these roots can penetrate, and should bathe them in the nutrient solutions carried by the soil water. One of the chief inefficiencies of present-day farming is that of applying expensive fertilizers to open soil. Potato growers in Aroostook County, Maine, have claimed that when the potato crop sells cheaply they do not get back the cost of the fertilizer they must spread on the land to produce the potatoes. Potatoes are mostly water, plus starch made from air and water, with the fertilizer elements entering as less than one per cent of the total weight; the discrepancy

seems to arise from the fact that most of the fertilizer is washed away.

Plowing is a problem in mechanics, but plows have been designed since the beginning of time by trial and error rather than scientifically. Even the modern tractor drawing a gang of plows behind it leaves much to be desired as far as efficiency is concerned. Electric plows with motors of 125 horsepower, drawing energy from their own transformers which are fed from 30,000-volt transmission lines, are fairly common in France. In other areas seven plows fastened together plow a strip eight feet wide, and are able to cover thirty acres in a day when pulled by 200-horsepower motors. The day of the stream-lined plow is coming!

The physics of the soil has been the subject of many books, but much is still unknown about it. Farmers know that some crops prefer a loose sandy soil, and others a heavy clay soil, but if they have a field which changes in composition from one part to another, and horsebeans happen to be the crop of the neighborhood, horsebeans are likely to be planted in the whole field. The methods of the present make any other course impracticable; with the methods of the future, ten times as many horsebeans will be grown on the most suitable tenth of the land, and the rest will be devoted to other crops or lie fallow.

The chemistry of soils has many dark corners still to be illuminated. Concentrations of certain elements so small as to be difficult to detect by ordinary analysis appear to be absolutely essential to plant growth. The spectroscope, discussed in a later chapter, is being increasingly used to detect the extremely small amounts of important elements present in soils. In some regions of the West vegetation in certain areas is spindly and apparently slowly poisonous to animals

which graze on it. Investigation has shown that this land has a deficiency of sulphur and an excess of selenium. Selenium atoms are chemically much like sulphur atoms, and although a plant can tell the difference, if it cannot get the sulphur it wants it will absorb selenium, which appears almost as good. But the selenium is very harmful to animals. With the usual methods of analysis, long and tedious procedures are required to measure the sulphur and selenium contents of soils. But since the sulphur and selenium atoms give out very different spectrum lines, the spectroscope can be used quite readily to differentiate these substances.

Each pound of vegetable matter produced by an ordinary plant requires that it evaporate forty gallons of water. The yield of some crops is at certain periods extremely sensitive to water application. A variation of two inches in the July rainfall in Ohio is said to cause a variation of $13,000,000 in the value of the corn crop in that state alone.

A century from now a farmer who relies on rain to provide the water for his crops will probably be considered as old-fashioned as we consider the primitive man who harvested his crops wherever he found them in the wild. Rain is too likely to fall when it is not wanted, and not to fall when it is wanted. This does not mean that we should ignore the rain and irrigate our fields regardless of the contributions of the heavens, for a good rainstorm releases water that would cost thousands of dollars to pump and apply. But there is a great deal science can do about helping to solve the water problem. For one thing, it can find out how better to predict the weather. Again, it can develop sources of cheaper energy for taking water from regions where there is too much to regions where water is lacking. Floods and drouths are disagreeable only when they are kept apart; mix a good fat flood with a

long shriveling drouth in the proper proportions and excellent farming conditions result. Storage facilities are all that are required to do this.

To pump 3000 gallons of water to a height of ten feet with the best hand machinery requires an hour of a man's time; unless his time is not worth more than one cent an hour he would do better to use an electric motor, which could do the job in five minutes at a cost of less than a cent. Larger jobs can be done with a Diesel engine at even cheaper rates; sugar beets have thus been fed 73,000 gallons of water in an hour from a well sixty feet deep with fourteen cents' worth of fuel.

¶ 4

According to the estimates of Government entomologists, insects each year cause a loss of nearly two billion dollars in the United States, a sum equivalent to the earnings of more than a million men. Light, sound, and electricity are all being used to supplement chemical dusts and sprays in fighting insects on a physical basis. A high-power incandescent lamp suspended a few inches above a tray filled with kerosene-covered water in the center of a sixty-acre field resulted in the capture of about twenty gallons of insects in the first four nights of operation, after which the number of insects caught gradually decreased as the supply gave out. The rancher who used the method claimed that the light protected his beans, corn, and tomatoes, and entirely eliminated the need of sprays and poisons. Corn protected in this way was found free from worms. Ten cents per acre per night spent for electric light decreased the number of insect-damaged tomatoes from nearly half the crop to practically none; in another instance

three hundred dollars' worth of electricity produced light which increased the value of the tomato crop by two thousand dollars. A difficulty with this system for general application is that some injurious insects are not attracted by light, while others which are beneficial and necessary may be so attracted. It may be possible in the future to raise such worthy creatures artificially in a form which is not attracted by light; who can say that "Smith's Non-Phototropic Ladybugs" may not be a subject of future advertisements?

Insects can be killed by high-speed electrons shot from an evacuated high-voltage tube of a type designed by Lenard many years ago for experimental purposes in atomic physics. These electrons have been called death rays, but their use would be expensive and limited in application to insect control. A more effective insect death ray has been found to be the sound wave given out by a large electrical transformer near Boston. The hum of this giant carried far through the night, and was apparently mistaken by male mosquitoes for the mating call of a particularly alluring female. Whatever the cause, large numbers of mosquitoes appeared, only to be electrocuted and cast dead at the base of their electromagnetic Lorelei.

An electric fan sucking air into a bag placed under an electric lamp has been used to gather in a single night ten pounds of gnats, running hundreds of thousands to the pound. A little bit of this sort of thing would go a long way in gnat circles.

Oil-emulsion sprays, which work on a physical rather than a chemical basis, have been found very effective in controlling certain pests. A thin oil film plugs their breathing apparatus. Again, supersound, pitched too high for the ear to

hear, seems to have an effect on insects of some varieties, and may in the future be used to lure them to their doom.

To study the effect of wintry weather on the eggs of the gypsy moth, the browntail moth, the tent caterpillar, and numerous other insects, these have been treated in the laboratory to all the details of an old-fashioned winter within five days, under careful scrutiny of Government scientists. Information was quickly obtained regarding the relative abilities of foreign and domestic insects to stand severe cold.

5

THE PHYSICIST is able to aid the plant physiologist and the geneticist in rapid development of new species. Mutations, those startling dissimilarities of offspring to parent, can apparently be greatly increased in number by bombarding seeds with X-rays or with high-speed electrons or nuclear rays. Probably the electrons set free inside the seeds by the colliding rays bombard the genes which control the characteristics of the plant-to-be. With mutations greatly increased in number, artificial selection can be applied to breed new crops.

Bulb growers on Long Island have already adopted new varieties of double gladioli and double narcissi which have been produced by exposing bulbs to X-rays. A scientist of the General Electric Company has suggested that orange trees which would resist the cold might be developed in this way. Many freak varieties of plants have been produced—most of them valueless from an economic standpoint, to be sure, but all of importance in studying the processes of plant reproduction and variation. Many plants springing from seeds which have been subjected to the rays are found to be stunted,

while in some the life processes have been greatly speeded up. Grapefruit trees two inches high, for example, have burst into blossom at the tender age of five weeks. By the X-raying of bulbs, General Electric scientists have produced, along with less-desirable new varieties of lilies, a type of regal lily with anthers which do not shed pollen, greatly desired by florists. Such tentative results promise much for the future, but since for every Burbank there are a million farmers content to grow hay in the same rocky pasture that their fathers hayed before them, it is reasonable to expect that the agricultural revolutionist with the necessary Burbank-Edison combination of qualities may be slow in appearing.

¶ 6

Crop preservation developments which are now under way show vast possibilities. Chemical means of preservation such as smoking, salting, pickling, and preserving in syrups have long been used. Well-tested physical methods are: heating to kill bacteria and molds, followed by canning and bottling; drying and desiccation; coating with wax or grease to exclude air; and refrigeration. These methods, while preserving material in edible form, have usually caused some alteration in the product. No cold-storage egg can ever be mistaken for a fresh egg. However, modern research is resulting in increasingly successful new methods of preservation by refrigeration, and products have been preserved for years with little detectable alteration from the fresh condition.

One of the most promising refrigerating processes is that developed by Clarence Birdseye of Gloucester, Massachusetts, and others. Birdseye noticed that in the far north fish and

game which were kept frozen over long periods of time tasted quite fresh when thawed out. From this observation and previous work done by scientists he developed a process of quick freezing of fresh fruits, vegetables, meats, and fish. The basic idea of the process is to freeze the fresh material quickly, so that large ice crystals which might rupture the cell walls do not form. Very low temperatures are used; rectangular-packaged bricks of the cleaned food material held between metal plates are rapidly chilled under moderate pressure to thirty degrees below zero. Another quick-freezing method is the "Z" process, in which a finely atomized liquid refrigerant is used to remove the heat rapidly from the material being frozen. While some food materials do not respond well to such treatment, others after even a year in storage have a flavor and appearance, as well as a vitamin content, which make them difficult to tell from the fresh article. More than fifty food products, from oysters and lobster meat to corn-on-the-cob, when thawed after quick freezing have shown themselves deliciously edible.

While foods kept fresh by processes of this type can now be obtained in most large cities, the cost of refrigerated display counters and dry ice for storage has been an economic factor preventing more rapid spread of the use of such foods. Research has already reduced the cost of such refrigerators by three-fourths during the few years the method has been in existence, and the power required to operate them by four-fifths. Quick-freezing methods should be carefully distinguished from old-fashioned "cold storage," and even from the freezing of meats and milk which has been customary on shipboard for years. The essential improvement is the rapidity of the abstraction of heat from the food being frozen, to avoid change of flavor, and the use of refrigerants much

colder than ice. Cold storage was designed to prevent spoilage —the new methods are meant to preserve the quality of freshness indefinitely. Far from being less fresh than the so-called fresh fruits and vegetables purchased in city stores, the quick-frozen products are often fresher, having been cleaned and processed within a few minutes of harvesting.

An era in development of low-temperature food preservation similar to that which radio went through in the years 1900 to 1925 seems imminent. Today many millions of dollars' worth of quick-frozen food is being sold each year; as methods are improved, the cost of processing and storing the materials will decrease, and the economic importance of this industry should increase a hundredfold.

Before long we may expect to see large mobile freezing plants waiting in field and orchard to freeze at their ripest such crops as the cherry and strawberry. During the remainder of the year the frozen bricks of fruit may be dealt out as needed, to stand in the cupboard until the flinty cold within them thaws, whereupon they gently collapse in the dish into a pile of ripe freshness.

¶ 7

DEHYDRATION HAS LONG BEEN USED to preserve fruits like the prune and the apricot, and grass cured to form hay is as old as agriculture. It may seem strange that farmers can be taught anything new about hay farming after ten thousand years, but new methods of artificial curing now being undertaken show remarkable possibilities.

Hay is not merely dried grass, it is cured grass—by which is meant that certain changes produced by physical conditions

of heat, humidity, pressure, and air flow—other than mere loss of water—occur in the plant material. Almost two-thirds of the total grass weight must be evaporated as water vapor. Haying has always depended on the weather, but the age-old ready-made methods of cutting hay and leaving it to cure in the field are gradually retreating before the application of more controllable physical processes. Three British experimenters have found that they could greatly expedite and cheapen haymaking, and get a superior product, by piling the wet and new-cut grass around a wooden duct, in such a way that hot air could be blown through the pile. Using a five-horsepower motor they found it possible to cure a forty-ton rick of hay in thirty hours during typical English days of rain and fog. The hay commanded a premium in the market, as cattle were found to relish it more than ordinary hay.

Fan-made hay was found two-thirds as expensive to prepare as sun-made hay. The chief saving came from less handling of the hay, and smaller loss from weather. By installing thermometers in various parts of a large rick, the temperature changes, which are influenced somewhat by fermentation and curing of the hay itself, could be followed, and the experimenters were able to produce green- or brown-colored hay at will.

The silo is a piece of physical apparatus which produces, by the chemical reactions produced by fermentation, a highly nutritious animal food which will last all winter. Now comes the electric silo, with a current of electricity passed through the silage as the chopped green material is fed in by air blowers or belt conveyers. Up to thirty amperes of current are passed through the material, heating it and hastening fermentation. One such silo holds 3000 cubic feet of food and requires not over 480 kilowatt hours for processing. The silage

produced is said to be of an improved character, for the lactic acid bacteria which transform the fodder into silage, much as cabbage is transformed into sauerkraut, are given an advantage over the heat-dreading deleterious bacteria which impede the preservation process.

8

THE FARMER OF TODAY is likely to be interested not only in how to produce more and better crops, but also in how to dispose of the crops he has. Hence a most important consideration is new crop outlets. Many products previously wasted are made use of by the needs of new developments of physics. Acoustic treatment of rooms requires sound-absorbing materials which are now manufactured from such fibers as those remaining in sugar cane from which the sugar has been extracted. Drain pipes made from previously useless plant products are being fashioned with newly developed machinery. Cotton textiles are being used in road building—the tar covering protects the cotton, and the cotton acts as a binder. For air conditioning we must have filters, ducts, insulating materials, and structural materials, many of which can be made economically from agricultural products. The spinning of rayon made from cotton is a physical process. The microscope and the polariscope are being used to test and grade textile fibers so that they can be used in extended markets.

Though plants have learned how to accomplish storage of solar energy on a vast scale, they do so with an efficiency of only 1.2 per cent—that is, more than nine-tenths of the sunlight which falls on a plant is wasted. The fact that leaves are

green instead of black shows that they absorb only waves of light having certain lengths; and though we may be grateful to be spared so funereal an appearance of nature as would be presented by jet-black verdure, our hills and meadows are green at the cost of inefficient energy storage. Even so, agriculture is at present the most effective process man has of storing much of the energy which the earth is now receiving from the sun.

If methods can be developed for concentrating plant energy cheaply, so that it can be transported readily and used as a fuel which will compete with coal and oil, agriculture will take a great leap forward as an industry. Inevitably, earth-stored coal and oil must become less plentiful as time goes on; and since the efficiency of the processing of agricultural energy-containing products can be improved by scientific research, any process which will give a product whose cost is of the same order of magnitude as that of natural fuels deserves careful consideration, even though at present it may still be more expensive. Many chemists and engineers now consider not only practicable but economically feasible a process which changes the starch from potatoes, corn, and other crops into sugar, and then ferments this into alcohol which can be refined to give a motor fuel. On a straight cost basis petroleum motor fuels still have the advantage by a factor of three or four, but the alcohol products possess certain advantages which make their developers very hopeful.

Nearly twenty billion gallons of gasoline were consumed each year in the United States in the four years just before the recent war. Experts of the Chemical Foundation have computed that to replace this gasoline with alcohol containing equivalent energy would require the processing of nearly eight billion bushels of corn. Since the nation's en-

tire output of corn is usually only two billion bushels per year, if farmers want to continue to grow corn, and scientists can do their parts in development work, a continuing and expanding market should be available.

A cheap method of converting cellulose as well as starch directly into a concentrated fuel would assuredly put the farm into the lead as an energy producer, and forms one of the most hopeful methods of bottling sunlight for power. Then the entire cornstalk (or whatever plant is found to store sunlight most efficiently and rapidly), dissolved in great vats to give a liquid of high fuel value, would go forth to run the generating stations and the motor cars and locomotives of the nation, and the farmer would be launched in the power business.

Important contributions of science to the farmer may well be in the future, as they have been in the past, psychological. How great is the difference between the outlook of a man who has a stony field (plagued with bugs and containing a few bedraggled spears of corn or cotton), a mortgage, and an overworked wife and family, and that of a self-respecting citizen whose land, even if only an acre, is able to produce an assured and profitable income. One of the things most likely to bring about this change of outlook is the application to farm problems of the methods of scientific research.

As an editorial writer has observed, there are not many good wars in which a person may enlist, but the struggle against wild nature is about the best cause to which one may dedicate one's life. The methods of science go to the basis of farm problems; the methods of politics and economics, while necessary for temporary adjustments, can never do more than rearrange the surface aspect of affairs. One single basic scientific discovery can make unnecessary all the artificial solu-

tions to the plight of the farmer suggested by politicians and economists.

The telephone, the telegraph, the radio, the motion picture, and the automobile have already made great contributions, not only to rural living, but to civilized living in general. That science will make further such contributions is inevitable. Their nature can be surmised most readily by considering in greater detail the advances which have already been made.

III

SOUND RIDES THE WIRE

Now with one broad sweep the barriers of time and space are gone and all the world becomes our vocal neighborhood.

H. D. ARNOLD

FROM the standpoint of appreciating scientific achievement it seems a pity that the telephone has become such a familiar device. Here is the most sensitive scientific instrument ever made available for public use—the most valuable invention ever patented—so widespread that familiarity with it has bred, if not contempt, at least indifference! How pleasantly self-important a member of the human race should feel, as he deposits his nickel in the slot of a pay telephone and spins the dial, if he reflects that he has just set into action the most complicated mechanism ever devised by the human mind. Fifty million dollars' worth of equipment to be rented for five cents! And billions of dollars' worth waiting to be used for conversing around the world by anyone willing to pay for the privilege.

Along the wires now stretched across the earth travel thirty billion telephone messages every year, more than two billion a month, eighty million a day. At any particular moment—this moment—there are at least 100,000 telephone conversations going on. Nor do we merely 'talk over the telephone; we send telephoto pictures and radio entertainment

and teletypewriting over its lines as well. And for all this the world is glad to pay more than three million dollars a day.

Yet when the telephone first appeared it was called a scientific toy and an interesting device for professors. Newspaper editors placed it in a category with telescopes and balloons, which in those days occupied the place cosmic rays and atom splitting held in the years just before the first atomic bomb was exploded. The only reassuring voice to be found in the cold chorus of welcome to the newly arrived telephone was that of one optimist who thought it might turn out to be of some value to divers and coal miners!

We demand of the telephone that it enable us to talk on short notice with any desired subscriber, that it give us the right number at least ninety-nine times out of a hundred, that the conversation be understandable and reasonably private, and that either party to it be able to speak as soon as the other stops speaking. Since we are dealing with an extremely sensitive device which is occasionally dropped to the floor, it is not surprising that problems have arisen in making such an instrument rugged and dependable.

Today telephone engineers know how to arrange circuits so that hundreds of people can talk at the same time over a single pair of wires without getting their voices entangled, and long-distance lines have been installed to utilize this possibility. But even more remarkable is the fact that many a man who prides himself on being able to deposit a golf ball within fifty feet of where he wants it to go, at a distance of two hundred yards, can take for granted that he should be able on five minutes' notice to ring a bell in San Francisco or Sidney, and hit the right address every time at five thousand miles. Research showed how to attain such precision; development has made it practicable; control has brought it about.

2

ALEXANDER GRAHAM BELL was the Columbus of the telephone, and his story has been told so many times that here we need only recognize that his was the hand that drew together a number of the strands of physical discovery into an invention which greatly expedited human progress. Behind the development of that invention lies the story of how a piece of steel was trained to talk like a man. The telephone was given a voice which it has been using so effectively ever since that the far-flung tenuous network of its wires is now becoming the very nerve-system of civilization.

Bell has been called the Columbus of the telephone advisedly, for regardless of whether or not others crossed the Atlantic before him, Columbus gave the world a new continent. So all telephones which we use today are Bell telephones, whether or not any one of a number of other inventors was justified when he disputed Bell's claim to have sent the first conversation successfully over wires. Such questions of priority frequently arise in scientific fields, as in other fields of human endeavor; and whenever one individual is mentioned as being responsible for some accomplishment, it is well to remember that usually there are others whose claims are almost as great and sometimes greater, yet who, by some twist of fate, have been deprived of the heroic position which one man can hold, though a battalion cannot.

Bell, in any case, as a twenty-two-year-old was a genius who had a great idea, and he set about finding what he had to do to bring it to reality. His idea was that the vibrations which are produced when the sound waves of speech or music

fall upon the eardrum might be converted into vibrations of an electric current, which could be sent for great distances over the telegraph lines and then at the other end be converted back into sound vibrations. Actually it was a much better idea than Bell knew, as is evidenced by the fact that now men willingly pay a billion dollars a year to make use of it.

Bell got his knowledge of sound from his father and from the accomplishments of the famous German physicists, Helmholtz and Koenig. He consulted Sir Charles Wheatstone, an eminent English physicist, who encouraged him with enthusiastic advice. Joseph Henry, the greatest American physicist of the time, agreed that Bell had the germ of a valuable invention and advised him to keep after it. When Bell expressed the fear that he did not have enough knowledge of electricity to make his dream materialize, Henry told him to get it. Get it Bell did, and in the process of so doing he made himself into a capable physicist and mastered all the knowledge of sound and electricity that was available in his day. By his twenty-ninth birthday, in 1876, Bell had learned to make an inanimate diaphragm of iron reproduce the human voice.

Bell was perhaps lucky in not knowing too much about electricity in the beginning. Other inventors had the idea of the telephone long before he did, but most of them knew more about electricity than about sound, and failed to realize what had to be done to keep the sound vibrations in the proper shape while changing them from one form of energy to another. Bell, on the other hand, did not realize what tiny amounts of energy he was planning to control. If he had, he might have been too discouraged to begin. The current that eventually operated his telephone was infinitesimal

compared to that we now send through the smallest incandescent lamp. Today, with the vacuum-tube amplifier available to help us, we have much better means of handling such feeble currents.

We still use the telephone principle as patented by Bell, but the only part of the instrument that really resembles the one he designed is the receiver, and even this has been improved in many ways. As a result of fundamental research the magnet it contains can be made twice as strong and twice as durable (for floor-dropping purposes) as it was even twenty years ago. To get the true picture of modern voice transmission one must consider the things that other men have been doing to the telephone since Bell gave it to the world.

Today in the vast Bell Telephone Laboratories of New York City and Murray Hill, New Jersey, the leading research and development organization of the telephonic art, several thousand men and women are working on the telephones that we will be using next year, in ten years, and in thirty years. The technical engineers are testing newly designed transmitters which will screw into the present desk sets, new automatic switchboards which will give increased accuracy and rapidity of service, new transmission lines which will cut down the cost of long-distance messages. Behind these technicians are the development engineers and applied physicists, devising new filters to separate one telephone conversation from another on the same wire, hunting for new and better magnetic alloys. Behind them all are the physicists who are studying fundamental processes which have a bearing on sound and electricity. Usually they attack problems which can be made to tell why something behaves or misbehaves as it does. But those in charge worry very little over what

this fundamental work will bring forth, for in the past it has resulted in achievements worth far more than its cost, or than the imagination could picture in advance.

3

THE NOSE OF A HOUND leaves little to be desired for smell sensitivity, but for sensitivity to ordinary sounds the normal human ear leaves nothing to be desired. Measurements show that the average amount of power generated by a person speaking is less, if converted into electric power, than one millionth of that required to light a ten-watt lamp, yet the ear is so sensitive that this sound could be cut down another million-fold and still be heard. At least one eminent authority on sound believes that some persons who suffer from constant head noises really have nothing wrong except that their ears have such sensitivity that they are hearing the very motions of the atoms within them. All atoms are constantly vibrating because of the heat motion which passes across them, and sensitive detectors can make this ceaseless atomic surf audible at any time. Every one of us can almost hear unaided the motion of the atoms in his own ears.

The telephone transmitter, or electric ear, whose function is to change sound waves into electrical waves of equivalent form, need be but one millionth as sensitive as the ear, yet even that degree of sensitivity calls for care in its design and construction. Bell's original transmitter was soon scrapped in favor of one which proved to be more sensitive, developed by a number of other investigators. This carbon microphone transmitter can be made cheaply by the millions, though it is unsatisfactory for transmitting music or speech where faithful reproduction is desired.

The carbon transmitter has the great advantage of being hundreds of times more sensitive than any other type. Instead of requiring a sound wave to produce its own electrical wave, the transmitter furnishes the energy for this from a battery, and merely requires the sound wave to indicate what form of electrical wave it desires to have produced. Behind a thin steel diaphragm, which picks up the sounds, are packed thousands of grains of carbon in a mass through which electricity is trying to flow. Though constantly urged on by the battery, little current gets through this mass of grains because they touch each other so lightly, and the current can only flow through their points of contact. Now let the pressure of a sound wave push the diaphragm in, and although the carbon granules are crowded together ever so little, much more current flows. If the diaphragm follows the sound wave faithfully, the carbon-grain contacts, and hence the electric current variation, will do the same.

The best transmitter diaphragm moves only ten millionths of an inch under the impact of a fairly loud sound wave. Incredibly delicate measurements show that the individual carbon grains then move only a few billionths of an inch—the diameter of an atom! Small wonder that this type of transmitter sometimes gives trouble in the form of a hissing noise.

The wavy line with which Bell dealt and with which all other inventors dealing with sound are concerned is a line representing the variation in air pressure in the sound wave which is to govern the motion of the eardrum of anyone hearing the sound. The higher the hills and the deeper the valleys of the line, the louder the sound. The more hills arrive at the eardrum in a second, the higher the pitch of the sound. The smoother and more regular the hills, the purer the tone. Loudness, pitch, and quality are all tied up in the

single wavy line, and this line contains in its shape all any telephone need know about a sound wave. The transmitter should be able to change this wave into an electrical wave of equivalent form, and then at the far end of the line the telephone receiver should translate this wave back into a sound wave which is a replica of the one which fell on its transmitter.

Few persons have heard a telephone receiver (which is, of course, merely a diminutive loud-speaker, or electric voice) emit so perfect an imitation of the human voice that it would be confused with the original, yet this has been successfully accomplished with special apparatus in the research laboratories. It is possible to force an inanimate assemblage of copper, iron, cotton, paper, and rubber to say "Joe took father's shoe bench out" so realistically that the sounds cannot be distinguished from those of a human speaker. This tough sentence, together with its delicate companion, "She was waiting at my lawn," contains all the fundamental sounds of the English language that contribute to the loudness of speech, and the two are used regularly for testing high-quality telephone receivers. Such fine speakers are of course very expensive, and for routine telephony we must be satisfied with receivers which produce speech that is somewhat distorted, though understandable.

It is an old joke to express surprise that the same telephone that will convey English speech can also talk Japanese, Swedish, or Hindustani. This is no joke in the telephone laboratories. Most modern languages that are sent over telephones are similar in structure, and one goes as well as another through the imperfectly speaking transmitters that economy now forces us to use. But it does not follow that the clicks of the Hottentot language or the grunts of Australian Bushmen

would necessarily get through with sufficient clarity to be understood.

Every new type of transmitter that is developed is tested under all sorts of adverse conditions by having almost every conceivable syllable spoken into it. A careful check is then made to see that all get through safely. One girl speaks into the transmitter a nonsense syllable immersed in a typical sentence, such as, "Have the *guks* arrived?" Another girl in a different room gets the syllable from the receiver and presses buttons to record what she hears. Every time the keys she presses do not check with what was sent, as recorded by an automatic machine that supervises the whole performance, a black mark goes up against that transmitter. Originally the machine was allowed to make up the syllables entirely by chance, to insure that every conceivable combination of sounds would be tested. But it produced an occasional unfortunate monosyllable, and to spare the blushes of the operators human censorship was introduced, the sound combinations being made up artificially. Perhaps an inventor with a few idle hours on his hands may some day look into the possibility of going back to the mechanical syllable-former, with an automatic anti-blushing attachment which would toss out the offending syllable as the electric eye tosses out the blemished coffee bean from the sorting table!

There is another telephone job that is not automatic. Delegates to important international congresses usually find on the desks in front of them a telephone which can be plugged into any one of half a dozen holes. While the speaker on the rostrum discourses in his native tongue, his speech can be heard by telephone in English when hole number one is used, in French from hole number two, in Russian from number three, and so on. These various versions must, of

course, be spoken by interpreters from behind the scenes, for science finds the job of automatic translating still far beyond it, and is likely to continue to do so for some time.

4

IN THE DAYS WHEN THERE WERE ONLY A HUNDRED TELEPHONES it was easy to arrange to connect any instrument to any other. All that was needed was a hundred lines from these telephones to a switchboard, and an operator to connect any pair. Today, with 36,000,000 telephones in use in the world, more than half of them in America, the problem is even more complicated than it sounds, for 10,000 lines are all that can be bunched together on a board handled by a single operator.

In the first central stations the necessary connections were made by shouting boys, but these were soon replaced by quieter and more efficient girl operators. Now the human operators are gradually giving way to completely automatic exchanges operated by the dial system. This system is so reliable that fewer calls than one in a hundred go astray because of faulty apparatus.

When the dial on a hand telephone set is spun, a succession of electrical clicks goes over the line to the switchboard. The numbers so communicated are stored up in a mechanical memory device by a switching instrument, while it consults an electric traffic manual to find how best to route the call. When it has found the proper line to use, it makes the necessary connections and rings for the distant subscriber. If all possible lines are busy, it sends back the buzz so familiar to every telephone user. If something is out of order, or if one of its own contacts goes bad, it puts in a call to the

maintenance man and prints on an electric typewriter what it was doing when things went wrong!

The switchboard problem has taken much of the attention of telephone engineers, and their work has been greatly aided by the telephone physicists and chemists who have provided new principles of operation and new materials as they were needed. To arrange matters so that ten thousand wires can be inter-connected requires in some modern switchboards more than two million mechanical and electrical parts. The work of switching is done by electric motors which activate more than two hundred operations every second. Now, after more than sixty years of development, there are nine thousand patents on switchboards alone.

Though the apparatus in the switchboard rooms is getting more complicated as the engineers develop mechanisms to perform increasing numbers of routine operations, outdoors on the transmission lines things are becoming simpler. In 1910, the thousand miles from New York to Chicago was covered by the longest telephone line then possible. Then an invention perfected eleven years before by Professor Michael I. Pupin as a result of studies in mathematical physics made possible extending the long-distance lines. By placing magnetic coils in the line at properly spaced intervals, which helped the electric currents vibrate more readily, it was found possible to double the distance over which the voice could be heard, and a 2000-mile line from New York to Denver was constructed. This marked the limit of distance until 1915, when the vacuum-tube amplifier was ready to be put in the line to give the distance-weakened voice-signals occasional boosts to restore them to their original vigor. The culmination came in 1935 when telephone officials demonstrated

their ability to talk to themselves and to each other 23,000 miles around the world.

Not only has the total number of telephone lines increased, but the number of wires required for most long-distance lines has risen from one to four. At first a single wire was enough for each instrument, the current being returned through the ground. But the currents so free to wander picked up noise, and more than half the time, even on short lines, the faint voice sounds would be completely drowned out by all sorts of bangings, rumblings, and other earth-made static. Most of this noise was eliminated when two wires were used. Then came four wires, two to carry the caller's voice to the listener's ear, and two more to carry back the voice of the latter. This double-pair system is now standard for long-distance lines and would require the use of a good many extra millions of tons of copper wire if fundamental research had not shown how thin wires could be made to serve in the place of thick ones.

At first the old telegraph lines were made to serve for telephoning. Then special telephone wires were hung on poles until they blackened the sky in every big city. But when new amplifiers and other advances made it possible to reduce from the size of a pencil to that of a thread the copper wire required for talking a thousand miles, it became feasible to group several thousand of these wires together in a single cable as thick as a man's wrist. In this cable they now lie, carried on poles or interred underground, embalmed with wax and cotton and nitrogen gas, and buried decently in lead.

The long-distance line was at first so delicately balanced that an extra-warm day would upset it, but now this highly nervous aggregation of copper wires and vacuum-tube amplifiers has had so many checks and balances built into it that

in its most modern form it is quite unaffected by snow-storms and lightning flashes. The long-distance line furnishes an excellent example of the complexities frequently introduced into life by science that living may be simplified. As Dr. Frank B. Jewett of the Bell Telephone Laboratories once put it, "That many may be unaware, a few must be wary."

5

IN THE COURSE OF A PUBLIC ADDRESS, Jewett once gave an interesting demonstration of some of the accomplishments of long-distance telephony, letting the audience hear all that went on by means of a loud-speaker. To illustrate one point he put in a cross-continent call to a scientist friend in California, the voices of all the operators involved being clearly heard. After a friendly chat he then summoned half a dozen of his telephone colleagues to an inter-city conference by long distance. Their telephones were so connected that every conferee could hear everything that was being said, and could make comments at any time. The audience finally had the opportunity of hearing the speaker talk to them directly, and at the same time over a 1700-mile line from Cambridge, Massachusetts, to Charlotte, North Carolina, and back to Cambridge. Since his voice required an eighth of a second to make the round trip, everything he said could be heard twice.

The telephone has an unfortunate natural tendency to talk back to itself. If a transmitter is so placed that sounds fall on it from the receiver to which it is connected, it will repeat these sounds electrically to the receiver, which will again repeat them acoustically, and an endless chain will be set up.

A howling noise results, sounding as though the circuit were expressing anguish at the uncontrolled swirl of energy waves passing through it. To prevent this by keeping the transmitter from hearing the loud-speaker, it was necessary for the speaker to talk from an enclosed booth during this part of his demonstration.

Such protection alone is not enough, for some of the electrical waves bounce back whenever they hit an obstruction in the line such as an amplifier, and especially do they bounce back from the other end of the line. On short lines this reflection does not matter, for the echo appears so soon that it blends in with the original sound. But on the 1700-mile line the one-eighth second delay was just enough to mix the echo and the original speech in such a way as to blur the sounds completely. To overcome this effect sound engineers have devised the echo suppressor, a mechanical watchman which lets waves pass through the line in only one direction at a time. If all is quiet, the line is open both ways, but the first party to make a sound captures the line. The other party must perforce listen without back-talk until he can close the automatic switch his way by being first to talk after a short pause has allowed the line to open again.

In the line used by Jewett the speech was amplified by thirty-nine vacuum-tube amplifiers distributed at fifty-mile intervals. This was necessary because the thin wires now used weaken the voice waves so rapidly that after they have gone fifty miles they are less than 1/100,000th as strong as they were when they started. If the waves get too weak they will be lost completely amid the ceaseless motion of the electrons in the wires, so before they disappear entirely they are sent through an electron-tube amplifier, and are bolstered up to their original energy. Since these electron tubes are without

moving parts except for their flying electrons, it is possible to seal them up and leave them for months without attention.

If it were not for vacuum-tube amplifiers we could have no long-distance telephony of the type we now know. At first telephone engineers tried letting a receiver repeat the message into a new transmitter every hundred miles—the dying sounds from one stage being carefully picked up by the transmitter of the next and energetically started off again, to emerge enfeebled from the end of that stage, and be rejuvenated by the next. Such mechanical repetition was unsatisfactory because too many unwanted sounds got mixed in, and each time the message was repeated, its wavy line suffered such additional distortion that by the time it reached the end of its journey it was almost unrecognizable. The facile electrons, if properly controlled in the vacuum-tube repeater, re-energize the waves without distortion.

One of the largest numbers that scientists ever need use is required to express the degree of amplification that such tubes regularly produce in making audible in London the voice of a man talking in San Francisco. Two hundred and fifty-six vacuum-tube amplifiers build up each conversation, and since each amplifier increases the voice sounds about ten times, the sound intensity is raised by a factor of 10 with 255 zeros after it which number is so large it is scarcely worth discussing. But the voice sounds are neither louder nor softer when they arrive than they were when they started, for the vacuum tubes themselves keep the amplification automatically adjusted exactly to offset the energy lost on the way. What the tubes accomplish, in effect, is the compression of five thousand miles to five feet.

6

To get across the oceans the telephone has had to co-operate with the radio rather than with the underwater cable. There are at least 37 telegraph cables across the Atlantic, but one cannot string amplifiers all along them, for amplifier tubes must occasionally be replaced; and without amplification the voice signals would fade away completely before they reached the other side. Since the last cable was laid, research has shown how a cable with new magnetic materials built into it could be designed so that it would be suitable for transoceanic telephony. Such a cable may some day be laid, but in the meantime the voice must be carried across the water on the wings of radio.

Radio is very poorly suited for transmitting private messages. Since its waves spread everywhere it is much better adapted to broadcasting. In addition radio waves are unprotected from the banging and scratching of static interference. It is discouraging to attempt to isolate a radio conversation from the interruptions of the ten thousand lightning storms which rage each day over the surface of the earth and interfere as much as would an untuned million-kilowatt broadcasting station.

In spite of these difficulties transoceanic radio-telephony is now almost a routine matter. To insure privacy, the voice waves are scrambled up before being broadcast, and are unscrambled automatically at the receiving end before reaching the listener. The wavy sound-line is stretched, chopped, compressed, mixed, and otherwise abused until it is completely unrecognizable during transmission; when it is received each

one of the operations performed on it is reversed, and it emerges as good as new. This treatment insures privacy, but the static problem was not so easy to solve. Even it was finally brought under control by the use of frequency modulation, or FM, however.

What is probably the greatest single telephone advance since the vacuum-tube repeater, came to the verge of commercial use in 1937. This is the coaxial cable, which was first installed experimentally between New York and Philadelphia. Over this line a copper tube with a wire inside can carry 240 simultaneous conversations, an apparent miracle made possible by the crystal wave filter and the vacuum tube.

The problem which had to be solved was this: How can one combine the 240 wavy lines of 240 conversations into a single wavy line, send this over the long-distance wires, and then separate it into its original wavy lines at the far end? The first part of the problem is readily solved; the unscrambling is more difficult.

It is as though we were to take 240 inks of different colors ranging from red to violet, which we must pour all together into a pipe, let them flow through this pipe, and then hope to get the inks separated at the far end. To accomplish this feat successfully we must first invent a suitable method, and then find physical means to carry it out.

We can solve the ink problem by using carriers. Let us buy white porous marbles in 240 sizes. Then we will soak the biggest marbles in the red ink until the ink has all been absorbed, wipe them carefully, and dry them. The marbles of the next size we soak in the ink of the next color, and so on down to the violet ink which goes into the smallest marbles. Now send the marbles through the pipe; they will roll through, although we may need to change the pipe slightly to keep them from sticking at its joints. At the far end ar-

range holes so that all but the largest marbles will drop through into another pipe. From that, all but the second largest can be made to drop through into a third pipe. Two hundred and forty such strainers would automatically separate all the marbles into their size groups, and hence the inks into their colors. Now let the marbles of each color drop into separate water baths where the ink pigments will dissolve out, and we get our 240 different-colored inks, separate and uncontaminated, after having passed together through the same pipe.

Actually the telephone problem is even simpler. Instead of marbles, electrical vibrations are used. The biggest marbles correspond to vibrations of more than a million cycles a second, the smallest to 60,000 vibrations a second. Vibrations can be fastened together, just as ink will go into porous marbles. The ink of one color represents the wavy line of one telephone conversation. Each conversation is made up of sound vibrations ranging from 60 to 4000 vibrations a second; and when it is applied electrically to a 60,000-vibration carrier wave, vibration rates between 60,000 and 64,000 result. Another conversation is applied to a 66,000-vibration wave, and so on until 240 conversations have been applied to waves of different vibration rates. Then these conversations are all sent together over the transmission line.

At the far end electrical filters corresponding to the marble strainers separate the different numbers of vibrations, those from 60,000 to 64,000 vibrations a second going into one local line, those from 66,000 to 70,000 into another, and similarly for the rest. It is then as easy to separate the voice waves from the 60,000-cycle and other carriers as it is to dissolve the ink from the marbles, and the seemingly impossible has been accomplished.

But now that a method of carrying out the process is

known, there are still two things to worry about. The first is how to get a pipe to carry the marbles; for an ordinary telephone line will not permit million-cycle waves to flow over it very far. Research has shown, however, that high-frequency waves will travel along the line if one copper wire is made into a pipe and the other is put inside it, the two being separated by insulating material. The current must be amplified every ten miles, but this can be accomplished with vacuum tubes. So the latest two-way long-distance cable consists of two pipes wound up out of copper tape, with two small copper wires inside them, all bound together with insulating material in a lead sheath.

The second problem to solve is how to construct filters to separate the various carrier waves. Such filters can be made of ordinary electrical condensers and coils, but filters made from these alone are found to be insufficiently precise in their selection of the vibrations they transmit, and if used would allow the various telephone conversations to overlap and become mixed. This difficulty was resolved by making use of the piezo-electric crystals which had been found to behave so admirably as converters of mechanical energy into electrical, or vice versa. In this new situation the crystal vibrates mechanically in response to those electrical impulses to which it is tuned, but to the passage of others it interposes an adamantine barrier. But it is not sufficient merely to stick a crystal into a telephone line, for if this be done, too narrow a range of frequencies is let through. Calculations made by mathematical physicists showed how to combine a set of quartz crystals with condensers, coils, and other electrical devices to make a filter which would transmit just the vibration range desired in each case and strain out all others. So quartz went into the telephone system.

What a lot of human emotion we are thus enabled to pack into one small pipe! Coursing through the copper at 50,000 miles a second go mixed together perhaps a hundred business and personal conversations carrying good news and bad, the raucous laughter of a radio comedian entertaining millions, telephoto currents carrying the picture of an airplane landing across the sea, and currents sent by a stenographer to operate two dozen typewriters in as many cities. And flowing along beside these, as unconcerned as though they were not there, goes ordinary electric power to light the filaments in the vacuum-tube amplifiers and thus set free the electrons which are to amplify the wavy line which carries them all!

¶ 7

BEFORE LONG we may have the self-answering telephone. Most of us do not want this feature enough to pay for it, but when we do, it will be ready. Telephone physicists are improving for a similar purpose the magnetic recorder, devised years ago but never widely used. It appears that message-recording telephones will soon be in considerable demand, at least in newspaper offices. We can imagine the telephone ringing in an empty house, the receiver rising from its hook, and a steel tape starting to unreel while it records in magnetic form all that is being said. This recording it does by rearranging its magnetic iron atoms in such a way that the record of the wavy electrical line that is being fed to it is preserved. The tape is thus the equivalent of a phonograph record which will reproduce the original voice whenever this is desired. The steel recording tape has an advantage over an ordinary record in that it can be made to erase itself as fast as it gives up its

vocal load, and it is then ready to be used again, ten thousand times or more, without showing signs of wear. Moreover, the tape can speak as well as listen, so it would be possible to have it say, when the telephone rings, "Jones residence—this is the telephone speaking—Mrs. Jones is out, but will you leave a message?" As soon as it has recorded what the caller says, the steel tape curls up in its compartment with the message safely preserved in its internal magnetization, and slumbers peacefully until the bell rings again.

Research has made modern telephony possible; and the by-products of telephonic research have furnished many new developments for other fields, some of which will be discussed in later chapters. For the moment it is sufficient to note that the satisfactory manner in which the modern telephone performs its functions is the result of an intelligently planned long-period campaign of research, a campaign which illustrates how powerful is the combination of fundamental science, applied science, engineering, and the technical arts when their effort is thrown in a common direction.

The co-operation among telephone research workers is no less than that among the members of a good football team. Though Bell made the touchdown we have been considering, it was as the result of a multiple forward pass—Volta to Faraday to Morse to Bell. The game these players started is still going on. Every time the referee blows his whistle the cost of transporting the human voice goes down, while the voice travels farther, and can be heard more clearly.

IV

GLASS—MORE PRECIOUS THAN RUBIES

"So," said the Fairy Godmother, "the jewel turned out to be glass after all."

OLD FAIRY TALE

A DIAMOND weighing a pound may cost a million dollars, while a pound of glass may cost less than twenty cents. Yet measured in terms of value to the human race, glass is one of the most valuable substances we have, and is worth far more than any jewel ever discovered. When the physicist and the chemist have finished discovering all the new kinds of glass that can be made, it will be worth even more. No single one of the developments of science discussed in this book would have been possible without the aid of this hard brittle substance, fortunately transparent, which originally seemed useful only to let light in and keep the wind and the rain out.

Glass, before science took it in hand, was just glass. Now it has been developed in dozens of new forms and endowed with a hundred new talents. Tough glasses which retard the flow of heat are made into building bricks and coffee-pot handles. Resistant glasses through which electricity can push only with difficulty are formed into telephone-pole insulators and vacuum tubes. New and surprising varieties of glass show unexpected abilities when shaped into frying pans, fireproof cloth, and even into springboards for diving pools!

A two-inch cube of glass would be strong enough to hold up a loaded freight car, though such a task would strain a similar cube of almost any other material. A glass window only one inch thick can be so constructed that it will stop a machine-gun bullet. A man can stand on a surprisingly thin sheet of glass and feel no electric shock even though 10,000 volts are trying to push a current through him. A house made of glass bricks will lose heat to frosty outside air only half as fast as a similar house made of ordinary bricks. Because glass has a smooth hard surface, bottles and dishes made of it are easy to keep clean. With such valuable properties in so many important fields, small wonder that more than three million tons of glass products are used in this country in a normal year.

Because diamond possesses most of the virtues of glass and in addition is harder than any other known substance, one might argue that it is intrinsically a more valuable material. But glass possesses a quality even more important than hardness—its ability to flow like honey or congeal into stone at the will of its molder. Glass is not a solid like steel or wood or rubber, but behaves at ordinary temperatures like a liquid which is too chilly to flow. Thaw it out by raising its temperature a few hundred degrees and it becomes as easy to shape as taffy at a candy-pull. Heat it a bit more and it runs like syrup; cool it down and it grows viscous. An intermediate temperature can be found at which it will have the proper consistency to be blown, pressed, rolled, cast, drawn, or spun into useful form.

If diamonds a thousand times as big as the Kohinoor could be bought for five cents a pound, windows of diamond would still be too expensive to use. The panes could be formed only by sawing them out of solid chunks of diamond, an operation

much too expensive to be practical. Such sawing would be necessary because diamonds do not melt slowly like glass, but stay sparkling and hard up to the highest temperature they can stand. Then presto! they vanish in a puff of gas. This crystalline imperturbability is in sharp contrast to the tractable behavior of glass when heated.

Windowpanes can be formed from glass by blowing, this process having been improved through the years until great bubbles three feet in diameter and forty feet long can be pulled up on the end of a blow-pipe from a molten pool of glass. When such a huge glass balloon cools, it is cracked across the ends and down the side with a diamond, and the freed central portion is then heated again until it is soft enough to unroll and sag flat. This unrolling is likely to be uneven, however, resulting in the irregular bulges often seen in cheap windows. A more modern method is to pull a wide flat sheet of glass directly from the molten pool by laying a long pole on the glass surface and slowly raising it. Hundreds of millions of square feet of glass are produced in this way each year in the United States.

Plate glass, usually thicker and always more expensive than drawn glass, was formerly cast in slabs which were ground and polished with abrasives after they had cooled. Now plate glass is made by sending a continuous slab of soft hot glass between rolls, the resulting sheet being later ground and polished. This polishing operation is very expensive and cannot compare in convenience with the production of a smooth surface by blowing or by freezing a natural liquid surface.

Glass can be made out of hundreds of substances, ranging from the sand of a sea beach to sugar from a grocery store. Any material which can be melted and then cooled to rigidity without crystallizing will form a glass. Those jaw-jeopardizing

bits of transparent hard candy which children like are true pieces of glass, but windows of such glass would dissolve in the first rainstorm. A much more permanent variety is made by mixing quartz sand crystals with chemicals such as lime and soda, and melting them together to form a liquid stone which, when cold, is transparent, permanent, hard, and resistant to heat and electricity, properties which have been found so useful that without them our civilization could scarcely have reached its present form.

The arrangement of the molecules in a piece of glass or other material can be studied by sending through it a beam of X-rays and photographing the patterns which the X-rays form when scattered by the molecules. Such X-ray photographs show that in crystalline solids, like iron or diamond, the molecules are arranged in rows, columns, and diagonals as regularly as soldiers on parade. In a glass, as in a liquid, the molecules have no regular arrangement. Glass *can* be crystallized, by stirring it in the molten form when it is almost cold enough to set, exactly as crystals of sugar are formed when the housewife stirs hot fudge while it is cooling. This process is called devitrification—literally "unglassifying." But most of the valuable properties of glass are found to arise from the fact that, instead of being a normal solid, it is a supercooled liquid in which the molecules are willing to be frozen into random positions, without snapping back into their pattern formations; and crystallized glass is fragile and practically worthless.

The king of all glasses—fused silica—can be made by melting pure crystals of quartz, but it is unfortunately too expensive for most purposes; for quartz is hard to melt, and when it does melt is hard to handle. Fused silica makes the world's best telescope mirrors and, if the world could afford them, its best

frying pans; but a five-hundred-dollar quartz skillet is hardly a practical proposition. Scientists hope some day to make practicable and cheap the large-scale production of this almost ideal glass, but until they do we must, for most purposes, be satisfied with less versatile but very useful substitutes.

2

THE ART OF THE GLASS BLOWER has been developed to take full advantage of the mobility of molten glass. Members of this craft have developed amazing skill in handling a bubble of what looks like red-hot molasses on the end of a six-foot steel tube. To watch a glass worker twirl around his head a long rod carrying on its end a fluid drop the size of a football gives one an impressive demonstration of nonchalant dynamic equilibrium. When centrifugal force has pulled the mass out into a long pear, the blower will puff into his tube as he whirls it between his hands, then pat the bubble with a paddle of burned wood, and perhaps roll it on a steel table while he occasionally puffs again into the tube from that side of his mouth which does not contain a cigarette. When the bubble has begun to congeal he may snip at it with a pair of shears to trim off ribbons of glass now the consistency of cheese; a minute later the mass solidifies into the desired bulb or beautiful vase.

When Thomas A. Edison started work on his first incandescent lamp, he sent to the Corning Glass Works in Corning, New York, for the bulbs in which to house his glowing filaments. Edison had a fourfold problem: electricity must be sent into the lamp, light must get out, heat must not melt the bulb, and air must be kept out permanently. Bulbs of

glass fulfilled all these requirements ideally. Since then the demand for bulbs has grown from a hesitant start to several million a day in this country alone, and as new means are found for making them more cheaply, demand increases.

Though a good glass worker with a helper can blow from 500 to 1500 bulbs a day, most bulbs now made in America are blown by machines which can turn out as many as fourteen completed bulbs a second—over 800 a minute, 48,000 an hour, 7,000,000 a week. "Ah, more technological unemployment!" says the pessimist. Glass-blowing machines have put a few men out of work, but they have *made* work for many more. Machines blow most of the bulbs needed for radio tubes and lamps, but as a result of the improved and cheapened output the demand has so increased that more than enough hand-blowing remains on odd lots such as colored globes and other objects needed in quantities too small to be worth making by machine.

The development of automatic glass-blowing machinery shows how scientific control can achieve a result previously thought possible only by means of human skill. The blower must keep the glass from dripping off the end of his blowing tube, yet he must not let it collapse into a formless mass or congeal before he gets it shaped. The inside of a hollow vessel he molds with air pressure from his lungs, pressure kept steady by the nice adjustment of a leathery cheek which after years of use often resembles a bellows. To form the outside of the vessel he commonly uses a mold into which his bubble of glass can be inserted. This mold is in two halves which close together from each side like the halves of a clam shell, with a hole through the top for the stem of the glass to fit through while it is being blown. The blowpipe is spun

rapidly to smooth the outside of the glass object against a cushion of steam, formed when the hot glass comes in contact with the moist inside of the mold. The glass blower must control and synchronize the sagging and flowing of the glass in the bubble, the pressure of the air entering it, and the twirling of the pipe. If something goes wrong he must blow or twirl faster or slower to restore balance.

How could an inanimate machine develop skill to do this? Substitution of scientific control for skill turns the trick. The old-fashioned method would have been to imitate with a machine the motions of the man. The modern method is to study, measure, and install the operations needed to make a teaspoonful or a bucketful of glass almost automatically flow into a bulb or bottle of the desired shape. Only by such means are bulbs for fifteen-cent lamps made possible.

In one modern bulb-blowing machine a stream of syrupy molten glass flows from a hot brick faucet in the side of a brick furnace, down between two water-cooled steel rollers which flatten the glass stream into a viscous ribbon. One roller has indentations in its surface, which leave thick buns of glass spaced three inches apart on the ribbon. The glass in these buns naturally remains hot longer than that in the neighboring thin sections. The ribbon is carried along on a moving chain of steel plates, and in the plate under each hot glass bun is a hole. The molten glass sags through this hole to form a constantly enlarging pear-shaped drop. When each drop has grown to an inch in length as it hangs from the moving glass ribbon, a moving nozzle clamps down over the top of the bun and gently blows air against the hot glass so that the drop will expand and be thinned out into a bubble. Shortly thereafter two waiting sections of mold rise up from opposite sides to accompany the glass bubble; they close to-

gether about it as it moves along, and spin rapidly around it. The steam-lined mold gently rounds the outside of the still molten bubble into the desired shape, while the inside is constantly pressed outward by the air entering from above. Only air and steam touch the surfaces of the bulb, until within a few seconds the glass freezes solid and the two halves of the mold stop spinning, open, and return to repeat the operation on a later bubble, while the finished bulb rides along on its glass ribbon.

We have followed a single bulb, but should recall that bulbs were suspended from the glass ribbon at three-inch intervals; and as this ribbon is rapidly moving, several dozen bulbs in various stages of formation are constantly visible. When each finished bulb reaches a certain spot it is broken loose from the glass ribbon by a smart tap from an automatic mallet, after which it is deposited on a wide asbestos belt. There, with hundreds of its fellows, it rides slowly through a long annealing oven, where it is gently heated to relieve strains which might later cause breakage. The bulbs issue from the annealing oven in an endless stream, to be inspected and packed in racks by nimble-fingered girls. The still flexible glass ribbon, whose former bun sections are now empty holes from which the glass has been removed, curls its way down through a slot in the floor to be cast back eventually into the Devachan of the furnace for remelting and reworking, with the possibility next time of finding itself in a bulb instead of in the discard.

At one instant the glass is pouring out of the furnace in a molten stream. A few seconds later—and thirty feet away—the same molecules of glass have frozen into bulbs of exactly the size and shape wanted. It would be incorrect to say that a machine which can do this is almost human. So far as glass

blowing is concerned it is more than human—its abilities are those of 2000 men. Watching the human blower at work, one marvels at his control over the glass, at his ability to force it to conform to his will. Watching the machine at work, one feels that the tiny blobs of glass flow inevitably, almost joyfully, into the shapes desired. But their conformity is not entirely inevitable, as the man in charge of the machine will testify when something is not adjusted correctly. The smooth output of the machine is made possible only because the temperature and dozens of other properties of the glass have been carefully measured and are controlled with scientific precision.

Glass tubing is another product which is sometimes blown by hand, but which can be made much more rapidly and accurately by machine. A glass tube, whether used by an advertiser in a neon sign, by a chemist in his still, or by a physician in his fever thermometer, is a piece of a bubble of glass which has been drawn out to a great length before it could freeze, and then cut into shorter lengths which were finally reheated and bent into the desired form. When tubing is made by machine, many tons of glass are drawn out into one long bubble, the glass flowing continuously from a furnace through a hole which determines the tube shape. As the glass stream falls it thins as it hardens until finally, after going several hundred feet first vertically and then horizontally, it has congealed into a long tube of the desired shape and diameter. At the end of this tube four-foot sections are automatically cut off as fast as the tube grows. More than 400 miles of small tubing may come in a twenty-four-hour day from a single machine.

HEAVY TUMBLERS, GLASS ASH TRAYS, and thick glass cooking utensils are cast or pressed rather than blown. From a ribbon of glass issuing from the molten mass in the furnace, chunks of the proper size are cut off. These, looking like fiery meteors, go flying down chutes at dizzy speed to presses which stamp them to the desired shape in a mold. The finished pieces are then delivered to annealing furnaces through which all glassware must go if it is to be freed from the strains which are set up when it cools.

If a chunk of hot glass be left to cool by itself, the outside cools and hardens first and compresses the warmer inner portions. Such internal strains may remain unnoticed for years but, like set springs, they lie waiting for an opportunity to shatter the glass to fragments whenever a grain of sand or any sharp hard material nicks the surface of the strained glass ever so slightly. In the annealing process these strains are released harmlessly by holding the glassware at a fairly high temperature for some time and then cooling it slowly.

Annealing is a slow and expensive process, especially with large pieces of glass. Great telescope mirrors may require ten months to cool down, and as they must be kept at an average temperature of 750° F during that time, the fuel bill may be as great as one which would be incurred for heating fifty ordinary dwellings through a winter. Until recently the usual procedure was to anneal glass objects until experience showed that they probably would not break. But physicists have devised a simple apparatus which makes it possible to see directly, and even to photograph, the strains in a piece of glass.

Motion pictures of such strains, as they are being produced and released in the depths of a glass object, show how they can be controlled and eliminated.

The mixing of a new glass in a research laboratory is an exciting affair. The glass maker's hypothetical direction sheet might read something like this: To one hogshead quartz, for body and strength, add one-third barrel of soda, to help it melt. Stir in a bucket of lime so the glass will not dissolve in water. Now comes the time for imagination, with eighty-odd chemical elements to choose from. Shall we put in some borax to keep the glass from cracking when suddenly heated? Or a dash of lead to keep X-rays from getting through, or a pinch of barium to give sparkle? Then stir thoroughly, put in a pot in the furnace, and melt overnight. When ready, pour out into brick jugs, allow to cool slowly, and test.

Here is where the physicist of the glass industry gets his innings. He has many important questions to ask the glass. How close does it come to that ideal glass which will not expand at all when heated, and hence would never crack when suddenly chilled? Will it stay sparkling and clear when exposed to the weather for six months or will it dissolve in water so as to be fit for little but preserving eggs or pasting up wallpaper? How hot must it be made to get it to the state where it will flow like honey so it can be worked, and how much hotter can it be made before it gets so watery that it is hard to handle? These and a hundred other questions about the new glass must be answered before its maker can determine whether its formula is worth keeping or not.

A far-reaching development in glass research began when railroad trainmen had trouble with lantern globes which cracked when raindrops struck their hot surfaces. The scien-

tists of the Corning Glass Works realized that the cracking was caused by the contraction of the glass when it was suddenly chilled. They set out to develop a new glass which would change its volume less than one-ninth as much as ordinary glass does when its temperature changes. Fused quartz would be ideal, they knew, but impractical, so they must find new materials which would make the quartz sand melt as easily as the old materials did but would expand and contract less. They found that borax filled this need, but the first of the glasses they made with it dissolved in water. After seven years' work they had produced a number of glasses which not only expanded less than did the old glasses, but were more resistant to weather, heat, and electricity. These glasses became world-famous under the trademark "Pyrex."

Glass dishes have long been valued for tableware, but the older glass vessels would fly to pieces when heated too suddenly. The new Pyrex glass did not break when placed in the oven; and, after more years of research, still better glass has been found which will not break even when heated carefully on top of the stove.

When physicists studied the behavior of the new glass dishes inside the oven, they discovered something about cooking that neither they nor the cooks had imagined. It had always been supposed that a pie was baked largely by the hot air and the hot metal with which it was in contact. Exact measurements showed that baking is done mostly by waves of radiant heat traveling around inside the oven. The new glass utensils reflected the heat waves less than metal, causing more rapid and efficient baking. Also, when removed from the oven, food in glass dishes cools more slowly than that in tin because the glass holds the heat in. Users of such glass

cooking utensils have confirmed the findings of science, and in addition declare such dishes easy to clean and convenient to use.

¶ 4

IF GLASS WERE NOT SO BRITTLE it would be one of the strongest substances known. A thread of glass thin as a spider web can support a greater weight than can a steel piano wire of the same size. But when two large rods are compared the steel is stronger, for if steel be scratched nothing happens, whereas a scratch on the surface of the glass quickly spreads and the rod almost falls apart. The great desire of the glass maker—a flexible and elastic material which will give and bend like celluloid yet wear like glass—is not yet realized.

By varying its composition and treatment, glass can be made harder than steel or softer than the varnish on a piano. Some of the glasses developed for cooking utensils and telescope mirrors resist wear far better than steel. In silk-weaving factories the silk fibers rapidly wear away reels made of almost any metal; but reels made of resistant glass wear well.

Modern plate glass is sometimes subjected to a treatment known as "case hardening" which strengthens it greatly by taking advantage of the ability of glass to resist compression. Hot sheets of glass are quickly cooled so that the outside layers shrink first and compress the inner layers, but not so much as to cause the glass to crack. Since the internal layers are still molten these strains are gradually released by viscous flow, and when the entire sheet of glass has cooled to room temperature the outer portion of the glass is under compression, while the inside is under tension. The internal portion is then more sensitive to scratches than it would otherwise be,

but the outside, which gets the scratches, is less so. In this way sheets of glass five times stronger than ordinary glass have been produced. Since such glass cannot be cut through, beveled, or smoothed on the edge without shattering after it is tempered, the case-hardening process must be carried out on the final mirror or glass shelf.

Thin sheets of such glass on which a man can safely stand with only the two ends supported, while the glass bends like a perfectly tempered spring, are no longer a rarity. If strained past its breaking point this glass does not fracture into dangerous splinters, but breaks up into millions of small cubes which crumble apart as the internal strains are released. If used for steamship portholes this toughened glass makes possible as much as 60 per cent decrease in weight. In modern streamlined trains, dirigibles, and submarines, where lightness is of great importance, it finds useful application.

We usually see glass in sheets or chunks, but more than enough glass threads are spun each year to reach across the solar system. By dipping a rod into a molten pool of glass and then pulling it away rapidly, a single pound of glass can be drawn out into three thousand miles of fiber. The departing glass pulls a thin thread behind it which freezes solid almost instantly, and the faster the pulling is done, the finer will be the thread. By pulling the fibers out at more than nine hundred miles an hour, threads less than a tenth the diameter of the finest hair are produced.

In one glass-wool factory three hundred nozzles spin out more than seventy miles of glass fibers a second—six million miles a day. The fibers are piled together in a fluffy bat of inorganic wool which is sliced by great knives into chunks for use in insulating buildings, refrigerators, and hot-water tanks. A cubic foot of this wool weighs only 24 ounces. A layer four

inches thick placed inside the walls of a wooden house gives as much heat insulation as a wall of concrete ten feet thick. Glass wool is not rotted by moisture, and will retard the spread of fire, nor has any insect yet developed an appetite for spun glass.

These fine glass fibers can be twisted into yarns and woven into lustrous cloth which is fireproof, warm, and soft. The first fibers spun were coarse, and, as they broke easily, clothing made from glass cloth had many of the characteristics of a hair shirt. But by making the fibers finer they became more pliable and less likely to be broken, and if broken less likely to dig into the skin. Even so, glass cloth does not yet make completely satisfactory underwear, for glass fibers unfortunately will not stretch like wool or silk. Whether glass cloth will ever come into common use remains to be seen.

Glass retards the flow of heat so well that it makes an excellent building material. For keeping heat in or out, a wall of glass bricks one foot thick is as effective as a concrete wall two feet thick; as it becomes cheaper, glass as a building material should come into wider use. Nor need people who live in the new glass houses worry about throwing stones, for a stone will bounce off a glass brick quite as well as off an ordinary brick.

The new building block of hollow glass is a special type of glass brick which is translucent but cannot be seen through, for ribs on the inside scatter the light in all directions. It serves as a permanent double window which of course cannot be opened, but for which no sashes and frame are required.

COLORED GLASS CAN BE PRODUCED by adding to the molten syrup salts of various metals which absorb portions of the spectrum. Copper and gold salts give glass a red tint. Selenium gives the red tint which is much used for traffic signals. Silver, uranium, or sulphur in proper combination with other elements give yellow glasses. Iron and chromium can be made to give greens; cobalt gives blue; manganese gives amethyst; and with salts of some of the rare earths, brilliant new colors can be produced. Milky-white glasses can be made with aluminum and fluorine compounds. Attractive cameo and other color effects can be produced by fusing together into sandwiches thin sheets of glass of different colors, then sand-blasting to different depths through protecting screens.

The ability of glass to hold its shape is important to human health. When a physician calls on a sick patient, one of the first things he does is to revert to the role of a physicist and make temperature measurements. Few doctors and still fewer patients realize that the thermometer used is probably made of at least three different kinds of glass, and perhaps of five. If this thermometer were made of ordinary window glass, it might read 107° F when the patient really had a temperature of 98.6°, or, what would be more serious, vice versa. Grandfather's doctor did not know so much about fevers as our doctors do, principally because in his day no one knew how to construct a thermometer which would read the same all through its life if kept at the same temperature.

One finds glass in four-fifths of the instruments used by the modern scientist. Sometimes the glass serves merely as a win-

dow, sometimes it is a vital part of the apparatus. Always the instrument would be less accurate or less convenient to use if glass having the right properties were not available for its construction.

Though in recent years research has brought the glass industry far, first in Germany and more recently in America, much more remains to be done than has yet been accomplished. Thousands of useful new glasses await discovery. The architect and the sculptor can do a hundred times more with glass than has yet been tried. The builder of the future will want more, better, and cheaper glass. The astronomer swinging his eye through space, the physicist with his spectroscope, the chemist with his still and retort, the biologist with his microscope, the surveyor with his transit, the physician with his thermometer, are all clamoring for more, better, and cheaper glass. They expect the glass industry to continue to perform miracles.

V

LIGHT FOR A LIVING WORLD

Out of the darkness shineth the light . . .
Raising the pulse of the Cosmic Heart.
Mantrams of the Temple

THE sun, as a dispenser of energy, keeps the green world of vegetation alive, and hence indirectly the animal world and man. But the particular form in which this energy comes to the earth has made possible the development of a new sense, that of vision. As a result, man has come to depend on light of a particular range of colors to use as a probe, a subtle antenna, which he can stretch out into space, thus making an indirect contact with his surroundings that greatly extends his knowledge of his environment, and his control over it.

The sun, spreading its favors over the globe, can shine on only one hemisphere at a time, whereas we would prefer a twenty-four-hour period of only one-third darkness and two-thirds light. Though man has long busied himself with the problem of artificially lighting those extra hours effectively, only within the last sixty years has he learned how to produce a useful amount of light without burning something. Now he has found that the most convenient way to produce light is to convert electrical energy into luminous energy, and the result has been artificial light which is brighter, cheaper, more healthful, and more efficient than any that has previously been known.

Money spent for electric lighting goes not merely to pay for electrical energy, but for increased safety from fire, for more healthful surroundings, and above all, for energy delivered to the exact spot where it is wanted. If we used candles to light a modern home to the same level of illumination we now enjoy electrically, it would be necessary for the grocery boy to carry in more than half a ton of candles each month. Electrical transfer of energy through wires eliminates the smell of molecules which have been emptied of their energy in candles, oil lamps, and gas lights. Measured in terms of what a man can earn in a day, candles are cheaper than ever before in history, and more of them are sold than ever before, yet electric light has made candles a luxury in which most of us indulge only on festive occasions.

For reading and writing it is difficult to get sufficiently close to a candle to have it illuminate a page to proper brightness. The scientific unit by which quantity of light is measured is the lumen; an ordinary candle flame emits about a dozen lumens. At least five lumens should be shining on each square foot of page if one is to read without eyestrain, so to be read easily a book must be held within five inches of a single candle. Out-of-doors on a sunny day the light intensity may be as great as 10,000 lumens per square foot, and even on an overcast day it often reaches 2000. Yet indoors we usually read with intensities as low as one five-hundredth of these values. Imagine great-grandfather holding his book one foot from the four to ten candles required to give even this illumination!

When looking directly at a bright light, the pupil of the eye automatically contracts to decrease the amount of light received; and thus defended, the eye can cover a trillion-fold range of sensitivity between painful brightness and invisibil-

ity. A brightness of more than 10,000 lumens per square foot is too dazzling for comfort. The minimum brightness which can be seen is about ten billionths of a lumen per square foot. From this lower limit of visibility anyone who wishes to treat Portia's exclamation to Nerissa, "How far that little candle throws his beams!" as a literal question can readily calculate that, so far as the human eye can tell, a little candle throws his beams about a mile and a half.

The problem of the physicist who is trying to develop a new electric lamp has always been to find how to get the greatest number of lumens out of the lamp for a given amount of electrical energy, or number of watts, put into it; and to do this he must consider not only the various energy transformations—incandescence, luminescence, fluorescence, and phosphorescence—by which electrical energy can be converted into light, but also what kind of light is most useful to the eye.

The number of lumens in a beam of light measures how well it can be seen. By shining into the eye equal amounts of energy in the form of red, then green, then blue light, then the various other colors in succession, scientists have determined that the average eye sees yellow-green light five times as well as it sees orange-red, and sixty times as well as it sees blue-violet. Such relative insensitivity to certain colors is not what is usually termed color blindness, but we are all somewhat blue-blind and red-blind.

Our eyes have developed their sensitivity through the ages under the influence of daylight, which is sunlight mixed with light which has been made slightly bluer by scattering from the sky; and this daylight we call white. White light contains all the colors of the spectrum in definite though different proportions. If we require that our household lamps give white light, we are insisting that a certain proportion of the light

consist of colors which the eye does not see well. In fact, the requirement that a lamp give white light automatically cuts down its possible efficiency to about a third of what this would be if the lamp were designed to emit only yellow-green light, to which our eyes are most sensitive.

Measurements show that so long as our eyes retain their present sensitivity, 621 lumens are all that can possibly be obtained from one watt of power. An electric lamp of 100 per cent efficiency would then radiate 621 lumens for every watt put into it, but to do this it would of necessity radiate yellow-green light.

Thus a white light can never be 100 per cent efficient because of the red- and blue-blindness of the eye, which reduces the maximum possible output of any lamp emitting white light to 220 lumens per watt. But when white light is produced by heating a filament to incandescence we can never hope to reach even this efficiency, for hot filaments always emit a certain proportion of invisible infra-red and ultra-violet light. The sun itself radiates only 100 lumens per emitted watt.

The most efficient light, then, cannot always be the most satisfactory. Sometimes rather startling changes appear when we see familiar things under colored lights. Consider the expression on the face of a workman who sits down for the first time to eat his lunch under the glare of a mercury vapor lamp, when he looks at the meat in his sandwich and sees it a ghastly yellow-green in color! For delicate work such as threading needles or repairing watches light of a single color may be used to increase the acuteness of vision, but for our homes we want light nearly white. We need it to see things in their proper colors, although since evening has become psychologically associated with the soft yellowish tints of the

open fire and the candle flame, we may prefer the yellowish white of the incandescent lamp to a true white.

2

THE SIMPLEST WAY TO PRODUCE WHITE LIGHT is to heat a chunk of solid matter to incandescence. All kinds of matter in the solid or liquid form emit radiations of about the same color when heated to a definite temperature, and the higher this temperature the shorter are most of the radiant waves emitted. A cold stove is emitting radiant energy, but the waves are all too long to be seen, and are comparatively weak. Heat the stove and the radiation increases, the stove becoming first red hot, then yellow, then white hot. If the iron of which it is made did not melt, the stove would eventually turn blue hot and, at still higher temperatures, violet hot. At an intermediate temperature of about 12,000° F (which is approximately the surface temperature of the sun) the light emitted by the stove would be very like sunlight in color, and would fit the sensitivity curve of the eye closely. Matter which is cooler than 12,000° F emits electromagnetic waves most of which are too long to be visible; from matter hotter than 12,000°, most of the waves are too short. Thus the most efficient lamp in which incandescence is used to turn energy into light would be one containing a filament heated to about 12,000° F.

Unfortunately every substance we know melts or evaporates at temperatures far below 12,000° F, so lamp-development workers have been forced to content themselves with lower temperatures, and have had to try all sorts of dodges to make lamp filaments as hot as possible without burning them

through in less than the 1000 hours which is taken as the standard life for most lamps.

Inventors in Queen Victoria's early days spent much time trying to get light from ribbons of platinum or other rare metals, which they heated in the open air with an electric current. The first investigator to produce an incandescent lamp which burned long enough and gave enough light to be considered really practical was Professor Joseph Wilson Swan, a British physicist. Swan demonstrated one of his lamps at a meeting of the British Association for the Advancement of Science in Glasgow in 1876, and his invention was acclaimed with much enthusiasm. The prediction was freely made that the whole city would soon be lighted entirely by electricity. That this prediction had not been fulfilled twenty years later may be guessed from the suggestion of a punster of that time who pointed out that the *l* in Glasgow was still misplaced.

Swan's lamp was a good one, but he provided no effective way of bringing electric power to it. In America, Edison heard about Swan's lamp, got interested, and in typical Edison fashion set to work with a hundred helpers to develop an incandescent lamp of his own. In 1879 he emerged from his laboratory with a lamp which would glow for 45 hours with the brightness of a dozen candles.

Far more important than his contribution of an improved lamp was Edison's provision of central power-generating stations and a system of piping electrical energy around so that lamps (and later electric toasters and curling irons and washing machines) could be connected to wires independently of one another. This enabled any device to operate whether others were turned on or not. Before Edison made electric lighting available and desirable, all the energy used in the

average household was supplied in chemical form as food and fuel, or as the physical work of servants and laborers. The new lamp required electrical energy, which thus became available for dozens of other domestic purposes.

Swan's lamp and Edison's lamp were in principle identical. Both realized that if the strip of material which was to emit the light were to be heated by a reasonably small electric current, it must be thin and fine. They appreciated also that if such a delicate filament were not to burn up in the atmosphere as soon as it was heated, it must be protected from oxygen, so they placed it in a vacuum inside a glass bulb. Pumps which could evacuate a bulb at moderate speed were just becoming available in the 1870's, and much credit for making the new lamps possible should go to the German physicists Geissler, Toeppler, and Sprengel, who had developed improved pumps for removing air from containers when a vacuum was desired.

Filaments of carbon were used in their lamps by both Swan and Edison. Carbon was the material, of all those available, which could be made hottest without melting. Carbon filaments did evaporate, to be sure, slowly freeing carbon atoms which were deposited on the inside of the lamp bulb, thus causing the glass gradually to darken and absorb more and more of the light. But after Edison had spent twenty-odd years in improving the carbon filament lamp, he felt satisfied with it. By 1900 he had made the filament emit twice as much light for a given amount of electrical power as it emitted in 1880, and he had increased its average life of burning to six hundred hours.

Edison felt rightly that the result of his labors was good, but he made the mistake of announcing that the carbon filament lamp had reached ultimate perfection. If his lamp

were still the best available, our lighting bills would now be a billion dollars a year greater than they are—either that, or we would be getting along with one-tenth the artificial light that we now use. During every two-month period we save on these bills more than enough to pay for all of the years of research that have made the saving possible. Though the lamp was made practicable more than sixty years ago, it is still being improved through the efforts of hundreds of research workers.

The very year in which Edison announced that the ultimate in incandescent lighting had been achieved saw the birth of the General Electric research laboratory in Schenectady. In this laboratory, later to come often before the public eye as "The House of Magic" (to the amusement of its inmates, who recognize that such magic results only from hard work), researches have led to far greater improvements in electric lighting than even Edison had produced. As a result, the luminous efficiency of the incandescent lamp has been increased more than six-fold, and its normal span of life has been doubled. Edison's practical work made possible the hiring of physicists and chemists for fundamental research; their discoveries multiplied the practical value of his product not merely twelve-fold directly, but indirectly a hundred-fold.

[3

THE CARBON-FILAMENT LAMP gave much trouble because of the annoying tendency of carbon to evaporate long before it melts. Many scientists tried building lamps having filaments composed of metals of high melting point, which might be expected to last longer than carbon because of their slower

rate of evaporation. Tantalum and osmium filaments showed decided advantages, though osmium metal was so expensive that the burned-out lamps were bought back from their users so the osmium could be saved. Tungsten also was tried, but since no way of drawing tungsten wires could be found, the filaments were made by a process which was much like mixing tungsten powder into a dough with molasses, and then squeezing this through a squirt gun and extruding it like macaroni into fine filaments. An electric current was then sent through these filaments to burn out the binding material, but they were very flimsy, and when operated on alternating current they lasted only a short time.

In the General Electric research laboratory, in 1906, young Dr. William D. Coolidge was given the job of finding out how to make better tungsten filaments. He and his assistants set to work with the purest tungsten powder they could obtain, and tried heating and hammering it, drawing it through dies and sending an electric current through it while it was immersed in hydrogen gas—everything they could think of to get the grains of tungsten to cohere into a solid bar that could be drawn into a wire. At first their tungsten wires fell apart on the slightest provocation, but Coolidge persevered and at the end of four years he had found a series of operations which, when performed on the individual tungsten particles, enabled them to be drawn out into long thin threads; then by adding some thorium salts he was able to get these threads to hang together in a wire much as hemp threads hang together to form a rope. When Coolidge found how to draw fine and tough tungsten wires, a new incandescent lamp became possible—a lamp with a sturdy filament which would last over 1000 hours at a temperature sufficient to emit 8 lumens per watt.

To Coolidge grown older, director of the laboratory in which he carried out his researches on tungsten filaments, it must have been an impressive sight to watch miles of tungsten wire being drawn out in a great lamp factory. Before he applied his mind and hand to the problem, nothing would make the particles of tungsten stick together but a wasteful, ineffective, and damaging glue. Now, as a result of what he did, the tungsten powder, compressed while hot under a force of many tons, is heated almost to melting in burning hydrogen and rapidly hammered into a long thin pencil. This rod of tungsten can be fed at constantly increasing speed through one hole after another in successive die plates, each hole drawing the wire smaller until a stage is reached at which only diamonds will stand the strain of diminishing the thickness of the wire as it thins to the width of a hair. The final diameter of the wire must be controlled accurately to within a millionth of an inch. For some lamps, the wire must be drawn so fine that a single pound of tungsten is pulled out into forty miles of wire.

While the new filaments made possible by Coolidge's work were found to be strong, so that it was no longer necessary to plan for a large breakage loss in shipment, the lamps they made possible were still far from the lamps we know today. Another General Electric scientist was still to take an important hand in the brightening of the lamp. Dr. Irving Langmuir, since grown internationally famous for his fundamental discoveries in both physics and chemistry, and recipient of a Nobel Prize, set to work on the tungsten filament lamp in 1912 to see if he could discover anything of interest about its functioning and its limitations. Langmuir decided to find out whether the blackening of the bulb, which still occurred to

some extent in spite of the elimination of carbon, arose from some hidden gas or vapor.

Langmuir did not deliberately try to improve the lamp. He was told by Dr. Willis R. Whitney, then director of the laboratory, to find out what he could about whatever of interest went on inside the bulb of a lamp. Langmuir spent three years in merely investigating some of the processes that were going on in the evacuated bulb and in the filament. During that time he discovered facts which resulted in reducing the future electric-light bills of the world by several million dollars a day.

Langmuir found that since any water vapor left in the bulb ate away the hot filament, a drier vacuum improved the lamp. After he had eliminated all water he found that he could not make the vacuum much better without a great deal of trouble, so he went in the other direction and made it worse to see if that would increase the blackening. Contrary to expectation, he found that this made the filament last longer and decreased evaporation, provided the vacuum was made worse with some inert gas which did not react chemically with hot tungsten.

Langmuir reasoned that he might be able to reduce the escape of tungsten atoms from the filament by putting gas molecules in the way for them to bump into. For all the previous years of the lamp's existence, lamp makers had been attempting to improve the vacuum around the filament; what was needed was less vacuum rather than more, but an inert and drier vacuum! Langmuir filled the lamp with enough nitrogen or argon to bring its pressure when hot up to that of the atmosphere. Filling the bulb with gas not only made the filament last longer, but also decreased the blackening of the bulb, for the hot gases rising near the filament tended to carry

the evaporated tungsten atoms upward, away from the sides of the bulb, and deposit them where they would not absorb the light emitted by the filament.

Langmuir then compared the efficiencies of gas-filled lamps having small filaments and large filaments, and found that a large filament was much more efficient than a small one. He could not use large filaments in low-power lamps because the filament size controls the power used, but he had the inspiration to coil up a fine filament into a spiral. This made a small wire behave as though it were large, and cut further chunks from all future electric-light bills. Nowadays incandescent lamp filaments are made from wire which is first coiled once; then this coil is again twisted sharply into another coil.

Both Coolidge and Langmuir, during the course of their fundamental investigations on the tungsten-filament lamp, made other discoveries which resulted in practical accomplishments which have paid many times over for the cost of all their research work. These two men were researchers of the fundamental type both before and after they started work on the lamp, and their researches have all been open to charges of unpracticality if considered on a short-sighted basis. Instead of using brute-force factory methods to improve the lamp, they deliberately picked the problem to pieces and sorted these pieces out; then they deduced what things needed to be done, carried these out in ways which immediately became obvious, and produced results far greater than any which were expected.

Incandescent lamps with gas-filled bulbs and tungsten filaments are now manufactured with automatic machinery in hundreds of factories all over the world. One manufacturer makes lamps of more than 9000 types, and nearly a billion lamps are sold each year. Improvements in manufacture have

done much to reduce initial lamp cost. In 1910 a 25-watt bulb costing seventy cents was widely used; today we use for the same purposes a 75-watt bulb costing twenty cents. It gives ten times as much light as the earlier bulb, and in most localities costs no more to keep alight than did its dim 1910 predecessor.

Edison's best lamp gave 2.6 lumens for each watt fed to it. Some of the modern gas-filled incandescent lamps give 20 lumens per watt. But if 220 lumens per watt are theoretically possible, lamp development apparently still has a long way to go. This 9 per cent efficiency has given rise to many pessimistic and critical statements regarding the achievements of science in producing light.

To take such an attitude is like pointing to the extra-large hole in a large doughnut. If we need a certain amount of light by which to read at night, and willingly pay two dollars a month for electricity to produce it, and then someone doubles the efficiency of our lamps, thus cutting our light bill in half, certainly we should not argue that because wasting 90 per cent of the electrical power is almost the same as wasting 95 per cent of it, we are no better off than we were before. The cost of running a 30-candlepower lamp for one hour has fallen from six cents in 1880 to less than one-fifth of a cent today, partly because of the decreased cost of power, but mostly because of the increased efficiency of the lamp. That it is theoretically possible to reduce the cost ten times more by improving the lamp still further is cause for rejoicing.

¶ 4

SCIENTIFIC DREAMERS HAVE LONG TALKED of "cold light." In some far-off day (say the romantics) if man-made science ever

catches up with the insects, we shall have lights which give no heat, and shall bask beneath cool gleaming lamps of miraculous efficiency. Temporarily ignoring the reference to the insects, we may agree that this is not improbable.

Strictly speaking, there is no such thing as cold light. Light of any color is pure energy, and any material absorbing it will be heated. But the term is often used for light which has been emitted by a cool luminescent material instead of by a hot object such as an incandescent filament. The atoms and molecules of matter can be stimulated to emit light in a number of ways other than by shaking them with heat. When solutions of certain chemicals are mixed together, the molecules rearrange themselves and set free energy which appears as light, causing the whole mass of cool material to glow with a bright luminescence. Again, physicists have learned how to extract light from a fairly cool vapor, and by judicious sharp-shooting with electrons can cause atoms to emit light with scarcely a flutter in temperature. The development of a new type of light source is now resulting from the application of the secrets of atomic structure which physicists have ferreted out.

Many living organisms have been provided by nature with tiny lamps. The brilliant glow of some tropical waters arises from the luminescence of countless bacteria and marine organisms; various fish and insects also emit cold light. One of the brightest emitters is the flashing firefly, of which a variety common in Pennsylvania has been claimed to emit light at an efficiency which is 96 per cent of perfection.

The most efficient lamp, as we have seen, is one that will give yellow-green light; and fireflies and glowworms emit light of approximately this color. As a result, the simple lightning bug has been credited by at least one entertaining but misled critic with emitting light with his rump 8000 times as effi-

ciently as man has been able to do with all his science. Like some other good stories, this one is more interesting than true.

Physicists have analyzed the light of fireflies by holding successive insects in front of a spectrograph, each as it grew exhausted with its cheerful flashing being replaced by a fresh successor. (Child labor was later found more convenient for this purpose, the infant firefly larva in its innocence glowing continuously with fine co-operation until spent.) All of the light emitted was found to be concentrated in a very narrow band in the green where the eye is quite sensitive, with no waste energy in the red or blue, ultra-violet or infra-red, where the eye is partially or totally blind.

As far as human eyes are concerned, however, we must rob the firefly of a little of its vaunted 96 per cent efficiency. This figure, it develops, was calculated on the supposition that firefly eyes probably see best the light with which firefly stomachs glow. In other words, some of the firefly's supposed luminous efficiency comes from the assumption that nature would of course make the firefly efficient, which is no more necessarily correct than that nature should make the human eye able to see infra-red light because there is much infra-red light in sunlight. If we apply the narrow band of firefly light to the human eye, it is in the most efficient species only about 80 per cent efficient instead of 96 per cent, being a little blu-ish for the best seeing.

But this type of efficiency is not what we are interested in when we pay our electric light bills, and much confusion has arisen regarding this point. The firefly gets his high efficiency rating because most of the light he emits is very visible—it is well worth emitting. But nothing has been said about how much energy the firefly had to expend to produce this light,

and it is the power that goes into a lamp that must be paid for.

How many watts the firefly puts into its efforts to emit a lumen has not yet been exactly determined, but the estimates of competent biologists indicate that when its power expenditure is considered, the firefly as a light source has an efficiency of between one and five per cent, somewhat less than an incandescent lamp. And if chemists had to provide the luminous chemicals which the firefly generates, firefly light would cost thousands of times as much as light from incandescent lamps.

While the color of firefly light is efficient, its intensity is low. Calculations show that about thirty-six square feet of firefly luminescence would be required to give brightness suitable for reading in an ordinary room. For illumination of a whole room the entire ceiling and much of the wall space would have to be luminous. Then the room would be filled with an eerie green glow, and everything red or yellow or blue or violet would appear either faintly green or entirely black. There would be no shadows, and a person in the room would feel as though he were in a huge aquarium immersed in a tropical sea. Worst of all, color vision would disappear, and this we cannot afford to give up. Objects seen in black and white are far less discernible, in most cases, than are those seen in color, and if we used only black and green the seeing would be even poorer. Far less of a sacrifice than the loss of color vision is the loss of the three-fold gain in luminous efficiency which would be involved in using green light instead of white light. For most seeing purposes men will continue to prefer white light.

¶[5

BEFORE APPLIED PHYSICISTS could do a really intelligent job of making lamps brighter and light cheaper and more effective, the answers to two important questions were required. The questions were: What is light? and What goes on in matter when light is emitted? As a result of the great discoveries made in the years 1900 to 1930 regarding the structure of the atom and the nature of radiation, the physicist is now able to answer these questions.

Many kinds of electromagnetic rays have been discovered, all of which travel through space at the extraordinary velocity of 186,000 miles in a second. These rays differ principally in the length of the waves associated with them, and in the number of oscillations which an electrical particle through which the waves are passing will undergo in each second. The waves range in length from those more than a mile long, used in radio, to waves shorter than the X-rays, of which more than a million waves can be crowded into one inch. Only one very small class of these rays is able to affect the retina of the eye, and these we call light. The length of the waves governs the color of the light, and light waves range from the shortest violet, of which 65,000 waves are required to fill an inch, through the sequence of rainbow colors to the red, waves of which come 35,000 to the inch. Though there is evidence that owls, bats, and other nocturnal animals can see to some extent with infra-red radiation, the human eye is blind to waves longer than those which appear red, and to shorter waves than the violet.

When light is studied carefully it is found to carry its

energy in photons, little energy packets which have been shot out by atoms or molecules and travel through space on the wings which we call electromagnetic waves. Photons come in every size, from the tremendously energetic ones carried by the shortwaved X-rays, through those of less energy which we call light, down to the vanishingly small photons carried by radio waves. The question may well be asked: Does a beam of light consist of the waves or the photons? Some types of experiment give the answer—Waves! But just as many others say quite as emphatically—Photons!

The physics of light is not, however, in a vague and muddled state, as is sometimes said, with one group of scientists holding out for the waves and another for the photons. Nor is it begging the question to say that light consists of both waves and photons. A beam of light will show both its wave nature and its corpuscular nature if both are sought for, but sometimes one feature is more prominent than the other. To illustrate: When we see an eagle soaring overhead (usually, of necessity, in motion pictures), we are impressed with its winged nature, and when we see a penguin in the zoo we note its lumpiness, yet both eagle and penguin are winged birds with lumpy bodies. Radio emanations are like the eagle in that they have waves of such great length, and photons comparatively so small, that it is convenient to treat them as waves; X-rays are more penguin-like, with such short waves and such bulging photons that the latter characteristic is the more impressive. Perhaps we may say that visible light comes in the quail class—its waves are only moderately long, and its photons medium large. When the hunter is shooting at a quail he finds its wings to be its most important features; when he is eating the quail, he considers them one of the least important. So with light. When a physicist wants to find

where a beam of light is going he studies its wave properties; to find how energetic it is, he measures its photons.

In 1913 a Danish physicist, Dr. Nils Bohr, developed a new theory of the structure of the atom which explained much about how atoms and molecules emit radiation. Physicists knew that the simplest atom was that of hydrogen, consisting of a proton and an electron; Bohr found that by making certain assumptions he could predict, not roughly, but to closer than one-tenth of one per cent, the lengths of the waves of light which a hydrogen atom would emit when an electron bumped into it. Not only did his calculations predict light of wavelengths which had already been observed, but some new waves in parts of the spectrum which had not yet been studied were predicted, and when looked for, these were immediately found.

The essentials of the Bohr picture, which in qualitative form apply to any atom, are that a photon of light is emitted by an atom whenever one of its electrons has been displaced to another orbit from the orbit in which it normally wheels around the atomic nucleus. In returning to its original orbit the electron must give up energy, and this energy is radiated as a photon of light. The wavelength of the light emitted, and hence its color, will depend entirely on how much energy is involved in the transition from one orbit to another. Thus to predict what colors of light various atoms will emit, one need only determine the energy content of the various electron orbits in the atom. This spectroscopists have been doing for some years, so that for the most important atoms the energy levels are well known.

By firing electrons from a hot filament into a vapor, light can be produced very efficiently; for when an electron bumps into an atom it will disarrange the electrons of which this is

composed and give it the required extra energy to produce a photon.

When atoms are packed close together, as in a solid or liquid, the electron orbits get jumbled together and mixed, so that the easiest way to cause the atoms to emit light is to shake them all with heat; but this involves loss of control of the colors emitted. When atoms are in the vapor form, then, shooting at them with electrons will cause light to be emitted with very little wasted energy. The most efficient lamps of the future should be vapor lamps, and for special purposes such lamps are now coming into wide use. The physicist is not groping in the dark in his search for better light sources. He already knows how to produce fairly cold light, and he is beginning to do so in a big way with his new sodium and mercury lamps.

The papers on light production written by modern illuminating engineers and applied physicists emphasize the importance of atomic research in light production. These papers are filled with diagrams showing the energies of various parts of different atoms as deduced by spectroscopists and theoretical physicists, and are running over with the scientific jargon of photons and the quantum theory, words which had not been invented when Edison stopped working on the lamp, and which owe their existence wholly to the atom-probers of recent years.

6

THE GAME OF DEVELOPING A NEW MODERN LIGHT SOURCE usually starts with the selection of some usable type of atom which can be obtained in the gas or vapor form, and which, when bombarded with electrons, will emit light of a desirable

color. The yellow light of sodium, the blue light of mercury, and the orange-red light of neon have thus far been found most useful. There are not as many atoms from which to choose as one would like. If only a new chemical element were available, one whose atoms physicists themselves could design! New molecules made from our present stock of atoms may be found handy in this connection, and here we can take the firefly as a useful guide, for he has discovered some good ones.

The neon light of the advertising sign is easy to see, as it contrasts well with other lights, but it is rather inefficient to see by. The blue light of mercury has been used for some years to light factories and photographic studios, where its high actinic value is important. Recently the mercury atom has been put through a new course of training designed to help it emit white light instead of blue; and with tungsten and sodium, mercury appears about to share the honor of being one of the few atoms of the ninety-six varieties available which will be used to emit much of the artificial light of the future.

In 1932 the General Electric Company in America and the Philips Lamp Company in Holland simultaneously perfected sodium lamps for highway lighting. The sodium vapor lamp has attained the highest efficiency ever reached in a lamp of long life. Almost no invisible light is radiated by these lamps, and they often emit 60 lumens per watt, or three times as much as a good incandescent lamp. In sodium lamps well protected from heat loss, efficiencies as high as 300 lumens per watt have been reached. If sodium atoms emitted green light the lamp efficiency would be even greater.

The sodium lamp would have been developed much earlier but for a chemical difficulty. When hot sodium atoms come

in contact with glass they attack and blacken it rapidly; and it was necessary to hunt for some special kind of glass which would be indifferent to sodium. Several laboratories succeeded in mixing new types of glass which stood up well under the attack of the hot atoms, but these were all expensive. A transparent glaze was finally developed which could be spread in a thin layer on the inside of a cheaper glass, which would then be protected from the sodium.

Sodium lamps have been run as long as 8000 hours without being turned off, but it is found that turning them on and off once a day cuts the life approximately in half. They are called sodium lamps, but actually the gases which fill the tube are a mixture of neon and sodium, the function of the neon being to carry the current when the sodium is cold. The neon atoms outnumber the sodium atoms 10,000 to one; but since the sodium atoms respond more enthusiastically to the impact of electrons, as soon as they are released from the solid metal they emit most of the light.

To avoid wasting much energy in keeping the sodium vaporized, street-lighting lamps of this sort are jacketed in a vacuum flask like a transparent thermos bottle. Even with this expensive set-up they turn out to be cheaper to operate under some conditions than incandescent lamps, and as a result many miles of highway are taking on a warm yellow tinge at night. The yellow color makes vision more acute, and it seems likely that the increased brightness made possible by the sodium lamp may become an important factor in reducing the annual waste of a hundred million dollars and thousands of lives through accidents which are said to be caused by faulty lighting.

Sodium lamps for indoor lighting have been manufactured, and are highly efficient, but whether we shall ever be willing

to accept their yellow light for domestic lighting is questionable. Certainly, if we do, new cosmetics must be developed for evening use.

The mercury atom holds great promise of being the principal light emitter of the future. At low temperatures the mercury atoms in a tube emit a very blue light, but as the current through a column of the vapor is increased, the light becomes whiter. Since a column of vapor cannot melt, the vapor lamp has one distinct advantage over a filament lamp, but it suffers instead from the risk that the transparent container which holds its vapor may be melted or blackened. Since quartz melts less readily than glass, clear quartz tubes are used for the most efficient lamps. The Philips Lamp Works in Holland has developed small lamps in which mercury atoms held in a short quartz tube, with a hollow inside no larger than a pin, are made to carry such large electric currents that the pressure in the tube goes up to several tons per square inch. Under such conditions the tubes emit a brilliant white light, by far the most intense and efficient white light ever produced artificially. Lamps having twenty-five times the intrinsic brightness of an incandescent lamp filament have been run for one hundred hours before their quartz envelopes became too opaque to be useful, and lamps run at lower power but with longer life are now manufactured commercially. These lamps are tiny things, and if some way can be found to keep their quartz jackets from spoiling so rapidly while burning, a new era in electric lighting should appear. The life of the container remains the chief problem. This seems to be a physical rather than a chemical problem, for the alteration in the quartz appears to be a crystalline change caused by high temperature rather than a chemical reaction. Such lamps are now being used in motion picture studios, on

airport landing fields, and in many other places where light sources of high intensity are required.

A very important development in lighting involves catching much of the previously wasted invisible radiation from lamps and transforming this into visible light. Some lamps emit large amounts of ultra-violet light which does not penetrate their glass envelopes, and which could not be seen if it did. By coating the inside of the lamp bulb with a suitably chosen fluorescent powder, this powder can be made to emit light of almost any desired color under the impact of the ultra-violet light. Lamps using this principle are now widely available, and are being used increasingly for home and store lighting. Incandescent lamps treated with such fluorescent materials have comparatively low efficiency and brightness; but when a low-pressure mercury-vapor discharge tube is so coated, as many as 70 lumens per watt may be obtained, the fluorescence increasing the efficiency eighteenfold.

There are still many other tricks to be tried to improve lamps. If a mercury lamp tube cannot stand large currents, possibly it can stand quick pulses of current every hundredth of a second, giving the tube time to cool off a bit between flashes, but not giving the eye time to notice that the light flashes on and off intermittently. Several lamps of this type are under development, and it seems probable that in some way nature will be further outsmarted in producing the lamps of the future.

In the meantime the lamp grows brighter year by year, and its demands for energy grow less. The dark corners of the world—whether the lung of a baby who has breathed down a safety pin, or the hull of a sunken vessel fifty fathoms under water—are becoming easier to light. Behind this light, push-

ing back the shadows, we see the physicist in his laboratory, filled with the artistic satisfaction of having discovered how to persuade atoms to emit ten lumens where only one had gleamed before.

VI

THE RANSOMED ELECTRON

Ask what thou wilt, O my Master, for I am the slave of him who possesseth the lamp.

Aladdin and the Wonderful Lamp

ELECTRICITY has been harnessed by mankind for more than a hundred years, and we take for granted that it should push our streetcars, light our homes, and perform countless other useful and energetic tasks. But it is electricity flowing through wires which does these things, and such electricity, bound as it is to the atoms of matter and confined to flow through wires, is relatively as limited in its abilities as a laborer who can lift a heavy sledge-hammer, but who must be told frequently where to strike. When physicists learned that electricity can be set free from the matter which normally binds it—that the electrons of which it is composed can be distilled into a vacuum, there to disport themselves in unaccustomed freedom—new ways of controlling electricity were found which produced undreamed-of results.

To the original class of electrical servants—motors, dynamos, heaters—a new type of electrical foreman was added by the invention of the vacuum tube. As colonizers have learned the advantage of directing native workers through native bosses, so engineers soon found great advantage in directing electrical equipment through electronic vacuum tubes. Previously an electric motor required specific directions for each

desired operation, and could be guided in its operation only through coarse switches and controllers. With these a motor could be ordered to stop or go faster, and it would respond, but since vacuum tubes have become available to act as straw-bosses, only general directions need be given. Just say the electrical equivalent of "Arrange to have these street lamps turned on whenever it gets dark, and be sure to turn them off whenever they are not needed," or, "When the President touches this button, I want you to start these motors and make them open the needle valves that will start water flowing through Hoover Dam," and it will be done. That the electrons, which must boss the job, are among the smallest particles in the universe, while the eyes in the so-called needle valves, being eight feet across, are quite large enough for the Biblical camel to pass through, need not bother us. We can select vacuum tubes capable of releasing a sufficient number of electrons to control motors of any size. The swarm of electrons freed in even a small vacuum tube is so dense that if every electron were a locust they could darken the skies above an area covering half the Middle West. Yet this electron swarm can be controlled to make the tube a docile and amenable servant. To tell it what to do usually requires far less energy than is needed to raise an eyebrow, and the tube can respond in a split millionth of a second.

One of the great advantages of electronic amplifier tubes is that they co-operate amicably with one another, and will work well in tandem. They can be so connected that when one very sensitive tube receives a delicate electrical signal it can pass this along as a similar but stronger signal to a more powerful tube, which can in turn be made to actuate a still larger tube, and with only a few such amplifications the original signal can be magnified a million or a billion times in power.

Then clap your hands or whistle and the first tube will actuate the second, the second the third, and so down the line until the final tube of the series will govern as many kilowatts of power as may be needed to level a mountain or span the Pacific with speech.

Modern life is being revolutionized by so many agencies that it seems prosaic to add another to the list; but as the steam engine introduced an industrial revolution, so the electronic vacuum tube seems to be inaugurating an equally far-reaching change in our habits of living. That so simple an operation as pumping the air out of a small glass bulb containing a wire which can be heated, will set free an electrical genie capable of such feats as automatically turning on a fountain when we bend over to drink, or spontaneously bringing an elevator level with the floor, is impressive enough. But such useful tricks seem trifles when we consider the changes which are being wrought in the manner of living of millions of people by the subtle magic of this tiny lamp whose product is not light but electrons. Without such tubes we would have no X-rays, no radio broadcasting, no long-distance telephone, no talking motion pictures, no high-fidelity recorded music.

❲ 2

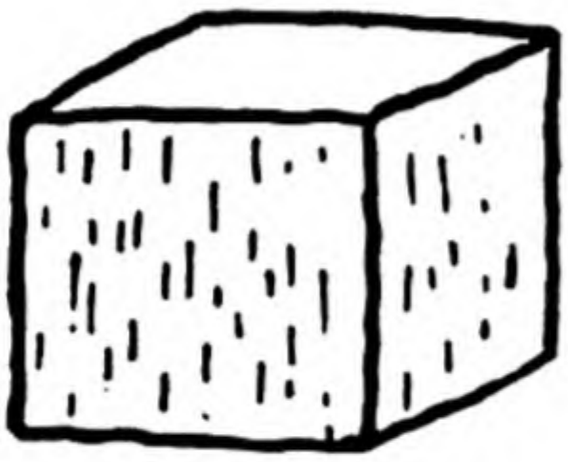
To aid in understanding the new methods of controlling energy which the vacuum tube makes available, let us consider briefly the various forms of energy and their relation to the levels of matter, as shown diagrammatically in the figures on pages 110 and 111. In imagination we shall penetrate the levels of matter, progressing from extreme diversity in the external world to relative simplicity in the world of atoms. As

the physicist has broadened his understanding of the structure of matter and energy, he has found that the ease of comprehending the relationships between its individual parts has continually increased.

The topmost level in the diagram represents our external world of everyday happenings. Though the object depicted is

THE LEVELS OF MATTER AND ENERGY

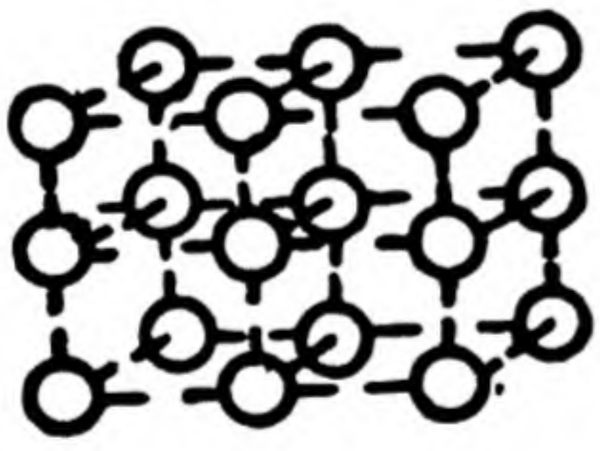
THE EXTERNAL WORLD, in which matter, appearing in a multitude of forms, is acted upon by mechanical, gravitational, electrical, and magnetic forces in varying degrees. It attains various temperatures, in accordance with the heat energy it contains, and is traversed by sound waves and by light waves.



ICE CUBE

Magnification: 1

THE WORLD OF SUBSTANCE, on which heat energy acts to give matter the form of liquid or gas or solid in the external world.



A CRYSTAL

Magnification: 1,000,000

THE MOLECULAR WORLD, in which several hundred thousand kinds of molecules gather into groups to form the world of substance; here heat energy is but the motion of the molecules, while sound waves are regular vibrations passing across the molecules.

A MOLECULE

Magnification: 10,000,000

an ice cube, it might equally well have been a table or a tree or a star or any other of the thousands of material forms with which we are familiar. On this external level of matter we deal primarily with mechanical energy, and ordinarily move matter about with mechanical forces. Actually, however, these mechanical forces are merely residual forces left over

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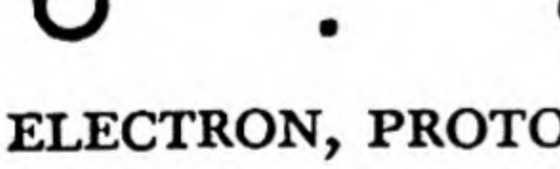
THE LEVELS OF MATTER AND ENERGY (*cont'd*)

THE ATOMIC WORLD, in which a few-score kinds of atoms group variously together in molecules to form all the varieties of substance with which we are familiar. Electric, magnetic, and gravitational forces hold these atoms together, and in the molecules so formed chemical energy is stored.

AN ATOM

Magnification: 100,000,000

THE SUB-ATOMIC WORLD, in which protons and neutrons gather in various numbers to form the cores of all the kinds of atoms, which are then completed when electrons in proper number are attracted about each core. Electrons and protons exert electric and magnetic forces on each other, and when an electron changes its speed of motion, electromagnetic waves such as light are emitted or absorbed. From these three fundamental particles of matter (proton, neutron, electron) all ordinary matter is formed, and from the three basic forces (electric, magnetic, gravitational) all ordinary energy arises.



ELECTRON, PROTON, NEUTRON

Magnification: 10,000,000,000,000

from a highly complex balancing of the more fundamental forces of electricity and magnetism.

Let us imagine that we possess a microscope which will magnify objects 1,000,000 times. Looking through this we find that the ice cube is composed of tiny crystals, which to our newly implemented vision appear as row on row of separate particles. We are now in the world of substance rather than of form, and find that objects differ greatly in the regularity of arrangement and in the separation of their constituent particles. The sound waves which traverse matter appear now as rapid mechanical waves which move these particles.

Increasing the magnification of our imaginary microscope, we find ourselves looking at the individual particles, and seem now to be in the world of the molecule. Molecules are the fundamental particles of which the different kinds of substance are composed; and each molecule is continually bouncing about. This bouncing energy we recognize as heat, though to the molecule heat is only extra mechanical energy.

Penetrating into the molecule, we find it composed of atoms. Some kinds of molecules consist of a single atom, some of two or more identical atoms, others of many kinds of atoms. But all of the different known molecules—some half a million varieties—are composed of only ninety-odd varieties of atoms, the chemical elements. On this atomic plane we are in the realm of chemical energy, for as the atoms combine together into molecules, they store energy in various amounts, much as mechanical energy can be stored in a coiled spring by compressing it.

Adjusting our imaginary microscope to look into an atom, we find it composed of a central core or nucleus which is a cluster of protons and neutrons, surrounded by a swarm of electrons. All of the ninety kinds of atoms which form the elements are built of protons, neutrons, and electrons in

various combinations. The atomic level of matter is the level on which electrical, magnetic, and gravitational forces are exerted.

All the multiplicities of the material world which our senses know are thus resolved into three fundamental physical elements—the protons, which are heavy particles having positive electrical charges; the electrons, which are light particles of negative charge; and the neutrons, heavy uncharged particles. (Such particles as the positron, the meson, and the neutrino need not worry us here, since they are not required for this simple picture of matter and their exact status in the structure of matter, is not yet clear.)

All the outer forms of energy—mechanical, sound, heat, light, and chemical energy—are manifestations of only three fundamental forms: electrical, magnetic, and gravitational energy. As a material finger is but a co-operative aggregation of protons, neutrons, and electrons, which wheel in their allotted courses as the stars wheel in the heavens, so when one presses on a table with a finger, the mechanical force which one feels is but an integration of electrical, magnetic, and gravitational forces. But if one wishes to move a piano, one does not trouble to compute all of the fundamental forces exerted on the constituent particles of the piano and one's hands. Instead of considering these, or the molecules of cellulose and steel which they form, or the cells of wood and crystals of steel which *these* form, or the boards and wires composed in turn of these cells and crystals, one considers only their mechanical integration, which is a piano, and the integrated forces, which are mechanical.

Sometimes, however, it is advantageous to operate temporarily on one of the sub-levels of matter. For example, the feeble ground vibrations from a distant earthquake must be enlarged if they are to leave a visible record on a seismograph

chart; and a simple arrangement of levers will produce such mechanical amplification directly. But such vibrations are relatively slow compared to those in some of the other forms of energy which our senses can detect, such as heat or sound or light waves. Even when direct methods of amplifying such waves are available they are usually slow-acting, cumbersome, and insensitive by comparison with the amplification of electric current waves which the electrons in a vacuum tube can accomplish. Happenings in the world of electrons are speeded up relative to human experience—atomic worlds explode, electronic meteors flash across space, in millionths of a second rather than in seconds. So it becomes of great advantage to be able to translate happenings on the human plane of living into changes on this subatomic plane. There waves can be stored, transported, or otherwise controlled, the results being later transformed back into our outer world of sight and sound. Where subtlety of control is needed, or rapidity of action, or automatic supervision of energy flow, the electrical world is usually very convenient to work in. And it is now becoming possible, by utilizing suitable transforming devices, to move from one form of energy to almost any other at will.

Conversion devices are available which will change almost any form of wave motion into the electrical form, and back into the original. The microphone, or "electric ear," converts sound vibrations into electric currents which it molds to conform to the wave form of the sound. The photo-electric cell, or "electric eye," turns fluctuations of light intensity into similarly varying currents. Once in the electrical form, electronic vacuum tubes can be put in charge of the amplification or control of any sort of wave motion. As a result of this ability, the electronic vacuum tube has become the most widely applied of all the numerous devices of modern physics. It has

enabled engineers to carry out many operations on the electrical plane which formerly they could produce only on the mechanical plane, thus putting into their hands tools of greatly increased subtlety and precision.

[3

THE FIRST THERMIONIC VACUUM TUBE was nothing more than an incandescent lamp with an extra wire sealed through its bulb. The curiosity of Thomas A. Edison was aroused one day in 1883 by a blue glow which he observed in one of the electric lamps on which he was working. When he sealed an extra wire into the bulb of this lamp, Edison found that he could pull an electric current through the vacuum of the lamp by charging the wire with positive electricity, but could not push it through in the opposite direction. A few years later Professor J. A. Fleming turned Edison's discovery to advantage by using such a tube as an electrical turnstile which allowed current to flow in one direction but not in the other. Fleming's device was found useful in the new radio-telegraph on which Guglielmo Marconi was working.

But it was not until 1906, when the vacuum tube was given its "grid," that it really came into its own. Dr. Lee de Forest was looking for some delicate electrical way to control an electric current—a sensitive method of indicating to the current how actively it should flow. When de Forest put into one of Fleming's electric valves a grid of wires which could be charged electrically, he found that he could govern the current flowing through the valve by means of a much smaller current sent into this grid. The grid was found to behave much like the throttle of a steam locomotive, with which,

using only the muscles of one arm, the engineer can control the energy of a thousand horses pushing its way from the steam boiler.

Soon the commercial possibilities of the vacuum tube began to be apparent, and it became the object of intensive investigation in several industrial research laboratories. Scientists of the Bell Telephone System under the direction of Dr. H. D. Arnold, for example, decided that such amplifier tubes might be useful in the long-distance telephone lines, and proceeded to improve them, with success which we have already seen.

Some of the early vacuum tubes were very sensitive to signals, while others which had been made in the same way were unresponsive. Dr. Irving Langmuir of the General Electric research laboratory found that this behavior was caused by variation in the amount of gas and moisture left in the tube when the air in it was pumped out. The vacuum pumps of 1915 were not so well-behaved and efficient as those of later years, and much of the magic of the modern tube comes from careful control of its vacuum. Tubes which are to be used with high voltage electricity require an especially "hard" vacuum—one in which less than one molecule remains out of every hundred million molecules of air which the tube originally contained. Tubes which are to carry large currents, on the other hand, have their vacuums purposely "softened" by the introduction of a small amount of argon gas or mercury vapor.

The widest use for electron tubes has always been in radio receiving sets. From three to thirty small glass-enclosed vacuums in which electrons are freed are needed for a single set, some to detect the incoming signals, others to amplify these up to the level of hearing, still others to change alternating

currents into uniformly flowing direct currents. In 1920 tubes for a radio receiver cost seven dollars apiece, and fewer than 100,000 were in use. Twenty-five years later the average tube sold for less than a dollar, and a hundred million tubes were needed annually to keep the radios of the world in operation.

In 1920 only a few varieties of vacuum tubes were made, and the general-purpose tube of that day can hardly be compared to the specialist tubes which later became available. But, like doctors who deal with the eye, ear, nose, and throat, some of these modern tubes are skilled in three or four diverse fields. The high-sounding names which they sometimes bear are merely Greek ways of telling what they can do. Thus "duplex diode high mu triode" is a fancy name for a tube which retails at about a dollar, yet will effectively perform the functions of four tubes of the 1920 variety costing seven dollars apiece.

By deflecting some portion of the current which has passed through so that it will return to influence its own grid, a tube can be made to set up electrical oscillations in wires which send out radio waves that travel for great distances and are now used to carry sound and speech through space. The more power a tube can radiate, the farther will these waves travel; so the electrons in radio transmitting tubes must carry large currents instead of the minute currents carried when signals are picked up in a receiver. This requirement has led to the development of huge tubes which will free millions of times as many electrons as are needed in a sensitive detector tube.

It is no mere flourish of words to call gigantic the entity which resides in one of these great vacuum tubes, for through a mere dozen of them may pass all the power with which ten electric locomotives pull as many fast freight trains. One large tube, developed for transatlantic telephony, handles two hun-

dred and fifty kilowatts of power continuously—more than enough to supply the ordinary electrical needs of fifty homes. Not the smallest problem in building such great tubes is that of fastening their glass parts to their metal parts so that no air will leak in at the joints. To get the large currents which must be controlled into the glass-enclosed vacuum without cracking the glass is the next problem. The metal cylinder used to gather the electrons which are freed in the tube would quickly become white hot and melt under their bombardment if a hundred gallons of water a minute were not used to cool it. Although an electron is one of the smallest objects which has yet been discovered, when a large crowd of electrons moves rapidly in one direction it can cut through steel like an oxy-acetylene flame.

Originally the bulbs of small vacuum tubes were made of glass by the technique developed for the incandescent lamp, but glass was not, of course, really necessary, since no light need get out. To encase the vacuum in metal would give a tube of increased sturdiness, make practicable a smaller bulb, and provide a desirable shield from electrical disturbances. Glass must be used to insulate the wires which carry electrons into and out of the bulb, however, and this necessity presented a difficult problem. Glass can be sealed to metal very easily, but a difficulty appears when the glass and metal change temperature, for if either material expands as much as one part in thirty thousand more than the other, strains are developed which will crack the joint. Furthermore, the two materials must expand together no matter how irregularly either chooses to behave. After much research both the Westinghouse and the General Electric laboratories developed alloys of iron, cobalt, and nickel which closely dupli-

cated the expansion of a suitable glass. Metal radio tubes then became practicable.

The fabrication of the new metal bulbs was made possible by the use of vacuum tubes themselves; in particular, of the sturdy young thyratrons, three-electrode gas-filled tubes capable of passing thousands of amperes when tickled electrically. The metal parts of the tube shells are welded together by sending currents of 50,000 amperes or more through the metal for a small fraction of a second. If a trifle too much current is used for such welding, the metal will be burned; if too little is used, the metal parts will not stick together: and in either case the tube will leak. Only an electronic valve could exert the delicate control needed to make such welding possible, and throughout industry thyratron welding is rapidly entering new fields. Three hundred thousand watts of power passing through one thyratron tube can be controlled with less than half a watt of power on its grid. Such an amplification of more than half a million times is equivalent to enabling a man to pick up a locomotive with the ease with which he would ordinarily lift a baseball.

¶ 4

WHAT ARE THESE ELECTRONS which have been freed from matter and effectively apprenticed for the use of man? On the day in 1897 when Sir J. J. Thomson, famous British physicist, found that electricity consists of countless charged particles, all alike, he could have had little idea of the many services which his new "corpuscles" would be performing for humanity a few years later. One or two simple vacuum tubes had been invented, but no one quite knew what made them oper-

ate or what to do with them. Thomson found that the vacuum in the tubes was filled with electrical particles which weighed far less than even the lightest atom, and these particles all seemed to be alike no matter from what kinds of atoms he drew them. Thomson discovered the electron when he succeeded in devising a method of weighing particles of pure electricity.

Since chemists take great pride in balances which are sensitive enough to weigh a pencil mark, one may well ask how Thomson was able to weigh something so light, so imponderable and elusive, as a single electron; something which, according to his measurements, weighed so little that a billion billion billion of them (10 with 26 zeros after it, or more conveniently, to save space, 10^{27}) were needed to register an ounce. If the ratio of weights is considered in each case, an electron is, in fact, as much lighter than a feather as a feather is lighter than the earth.

What Thomson did was to shoot a narrow beam of electrons across a large evacuated glass bulb and let them hit a screen coated with luminous salts, which glowed brilliantly at the spot where the electrons struck. Then he measured how far this glowing spot moved sideways when he pushed and pulled on the electron beam with electric and magnetic forces. Thomson found, strangely enough, that if all of the electrons were hurled across the vacuum with the same speed they would all strike the screen at the same point, no matter how he deflected them. This showed that they were all alike electrically.

We might use a similar method to sort out a packing case full of billiard balls mixed with basketballs. We could take the case to a playground where a long slide was available, and arrange to dump all the balls together down the slide. At the

bottom of the slide we could, by means of a large electric fan, blow a strong blast of air across the path of the balls. Now let the balls roll down. When the basketballs reach the air-blast they will be blown more to one side than the billiard balls, because they are larger in proportion to their weight. If hundreds of balls of assorted sizes and weights were rolled down such a slide, one could calculate just where, across a flat playground, one could expect to find rolling a ball of any given ratio of size to weight.

The experiment with the electrons is even easier to perform than that with the balls, because it can be carried out in a small evacuated bulb and the forces involved can be controlled more closely. However, we should not lose sight of the fact that if the electrons were enlarged to billiard-ball size, Thomson's vacuum bulb would stretch across the solar system.

The vacuum tube used by Thomson in these electron-weighing experiments has been developed into the modern cathode-ray oscillograph, with which electrical voltages and currents can be measured which are varying so rapidly that no material pointer could possibly follow them. The moving finger of the electron beam is made to write so rapidly on its scintillating fluorescent screen that the eye can follow only the trail of light it leaves behind. Some modern radio receivers contain tiny tubes of this kind called "magic eyes," which show visually when the set is correctly tuned. Thomson's tube has also been evolved further into the "Kinescopes" and "Iconoscopes" which make television practicable, as will be discussed in a later chapter.

Though Thomson's experiment showed the existence of electrons, and that they are all alike, it did not tell quite the whole story on the weight of the electron. To determine this

weight precisely required that the charge of the electron be measured—its electrical charge, which is merely a measure of how forcibly two electrons will repel each other when held a certain distance apart. To determine this charge, in 1910 Professor R. A. Millikan performed a celebrated experiment in which he trapped individual electrons on tiny drops of oil, which drops he could observe through a powerful microscope as they floated in the air. By measuring the electrical force required to make a given droplet rise instead of fall, Millikan was able to measure the electrical pull on the combined drop and electron, and hence the charge which the electron carried.

No research scientist knows when he may stumble on something startling, something which may profoundly affect human progress. In 1927 Drs. C. J. Davisson and L. H. Germer of the Bell Telephone Laboratories discovered that electrons have waves which steer them about in space. Theoretical physicists had found a few years previously that if electrons should possess such waves, a number of mystifying bits of atomic behavior could be explained. But Davisson and Germer were not looking for electron waves when they found them. They were merely trying to see what would happen when electrons were bounced against a piece of nickel in a vacuum. A surprisingly large number of the great experimental discoveries have thus been made by scientists who, while following the direction in which their curiosity led them, have unexpectedly beheld a great truth lying in their path.

The discovery of electron waves had immediate practical results. Light waves had been used in the microscope for years; why not a new kind of microscope which would operate with electron waves? That we cannot see electron waves did not bother the physicists, for they knew an electrical image

could be made visible by some sort of energy transformation. The scheme worked; by shooting electrons against surfaces which cannot readily be studied with ordinary microscopes, many new secrets of matter are being revealed. Even paints and printing inks, stainless steel and glass, are being studied with electrons bouncing around in vacuum tubes—with electron microscopes.

¶ 5

One lone electron is rather an insignificant creature, but when a big electron crowd is assembled it can exert forces which will drive ships across the ocean or flash thunderbolts across the sky. Hence the academic-sounding job of pulling electrons from atoms, as corn is shelled from the cob, has great commercial importance. Electrons pervade all matter and can be obtained only from the atoms of matter. Though every atom must be paid an energy ransom for any electron that it releases, some types of atoms drive a harder bargain than others. How can electrons be freed most cheaply? has come to be a question of great economic importance.

In the research laboratories of the colleges and of such industrial organizations as General Electric, Western Electric, and Westinghouse, where most of the development of the modern vacuum tube has been carried out, improvements in the efficiency with which electrons can be released from matter are still being made. Such research has already shown how to free twenty times as many electrons for a cent as was possible thirty years ago.

The simplest way to set electrons free is to heat in a vacuum a filament of tungsten or some other tough metal until some of its electrons boil out like smoke particles

streaming from a log of green wood in a fire. Such electrons are called thermions, since they are ions—electrically charged particles of atomic or subatomic dimensions—produced by heat. The hot filament of an incandescent lamp, for example, emits thermions in countless millions until the space around it is so filled with them that no more can emerge. In a vacuum tube these freed electrons are pulled across the vacuum and sent flowing to work through external wires, and the supply is constantly replenished from the hot filament. In 1910 a tungsten filament heated by a current of two amperes could be made to release three hundred billion billion electrons every second, which comes to two hundred billion billion electrons for a cent. This makes electrons sound pretty cheap, but since the work of the world begins to need a great many of them the twenty-fold increase in efficiency which has come from improving the filament results in a saving of over $12,000,000 a year on power bills to run radio sets alone. In one year we thus save more than enough to pay for the entire cost of the research which made the saving possible for all time.

It has been found that the atoms of which our material world is made are composed of tiny hard cores about which circle groups of electrons, a definite number of electrons in each kind of atom. Normally the core or nucleus of an atom is surrounded by exactly the right number of electrons to neutralize its charge, but if forced to do so by electrical pressure the atom will temporarily give up one or more of these electrons, though it will replace them at the first opportunity. Some atoms release electrons more willingly than others, and one of the jobs of the physicist in recent years has been to measure the forces with which various atoms hold on to their

electrons. The results of his findings were immediately applied to the improvement of the vacuum-tube filament.

A sulphur atom, for example, was found to be a rugged individualist which holds tenaciously to all sixteen of its electrons, while a caesium atom was found to be most cooperative in willingly sparing one of its fifty-five electrons. Obviously sulphur should not be used in vacuum-tube filaments, but caesium seemed worth investigating. Caesium metal melts on a warm day, however, so it could hardly be used for making red-hot filaments. But when a layer of caesium salts one molecule thick was spread on an ordinary tungsten wire, this was found to emit clouds of electrons while the filament was still relatively cool. Thorium was found to behave in much the same manner: when one per cent of thorium oxide was added to tungsten of which filaments were to be made, a single layer of thorium oxide molecules kept oozing out to keep the filament coated, and at a bare red heat 100,000 times as many electrons swarmed out in a second as had come from pure tungsten. This made possible the production of new tubes which required less power for their operation and which lasted longer before they burned out.

More important than either of these advantages was the fact that it now became possible to take electrons, not directly from the filament, but from a thin metal tube coated with electron-emitting salts, inside which the filament could be placed for heating purposes. Vacuum tubes, instead of requiring expensive current from inconvenient batteries, could then be heated with cheap alternating current from the lighting mains. This improvement made possible the operation of a radio set from a wall power outlet without introduction of an objectionable humming noise; radio receivers at once came within economic reach of additional millions of families.

They must have wanted them, for within a few years there were 37,000,000 radio receivers in 24,000,000 of the 32,000,000 homes of the United States.

When a modern radio receiver is turned on, the sounds from it increase in loudness as the tube filaments slowly heat the electron-emitters and electrons stream out in increasing numbers. Nowadays the filament in the tube glows but dully, yet from each square inch of its hot surface flow more than ten billion electrons in each second, electrons set free scientifically and cheaply.

¶ 6

SOME VACUUM TUBES respond to light signals rather than to electrical signals, and these have been popularly dubbed "electric eyes." Scientifically they are known as photo-electric cells and technically as phototubes. Without these inanimate watchers, talking motion pictures would hardly be possible, for such tubes are needed to help convert the light-variations on the sound-film into speech and music; the movie industry now uses 100,000 phototubes a year. Such a tube can be made sensitive enough to detect light which is invisible to a human eye, and to respond electrically to a change in illumination far slighter than any real eye could hope to detect. Since it will also respond a thousand times more rapidly and reliably than the fastest human being, it can often be applied effectively to jobs in industry where men would be slow or careless. Many a workman operating a great press still has two arms because a phototube which was attending to business held the power off when his arm got in the way.

The photo-electric vacuum tube has been in existence for many more years than has the thermo-electric vacuum tube.

In the phototube the electrons are freed from their parent atoms by the light itself. The fact that light can free electricity from matter was discovered in 1887 by the same Dr. Heinrich Hertz who discovered the ether waves which made radio possible, and in the course of the same experiments. How the electrons are freed by the light was explained by Professor Albert Einstein of relativity fame, and the explanation he gave, for which he was awarded the Nobel Prize, forms one of Einstein's greatest contributions to physics.

The first phototubes were comparatively insensitive and erratic in their behavior, but when such tubes were found useful in developing new million-dollar industries, intensive research was started which in five years had made the tubes ten times more sensitive, as well as stable and dependable in operation. Theoretically, phototubes can be made at least a hundred times as sensitive as they now are, so physicists are challenged to find how better to free electrons from atoms by means of light waves.

The phototube makes a very effective partner for the thyratron, that unobserving but powerful member of the electron-tube family. This tube has one principal reaction—to allow a tremendous burst of current to flow whenever it feels a tiny twinge of voltage. Such a twinge the phototube will supply when light falls on it, and the two tubes are often found together, resembling in relative size and strength a circus elephant being led by a diminutive equestrienne.

Set a phototube to watching beans or cigars or oranges or cakes of soap as they pass by it on a belt conveyor, and it will rest unconcerned so long as the normal amount and color of light are reflected from these objects. But let a browner bean appear, or a blacker cigar, a greener orange or an unwrapped cake of soap, and quicker than a wink it gives an

electrical nudge to its great dull thyratron partner. The thyratron is blind but it responds with alacrity to the one signal which can stimulate it; it feels the tweak of voltage from the phototube, brightens up, and immediately spurts a burst of current through an electromagnet, which quickly jerks a lever and kicks the offending article to one side in a thousandth of the time required to tell about it.

7

THE VACUUM TUBES OF TOMORROW will be as much more accomplished than those of today as the present automobile excels that of 1910. An entirely new principle of electronic amplification which is now approaching perfection promises much. The vacuum tube called an electron-multiplier, which utilizes this principle, combines in one small glass bulb the functions of a phototube and a dozen amplifier tubes. A tiny swarm of electrons, which is set free when a faint light beam strikes a sensitive surface inside one end of the tube, is pulled across the vacuum by electrical forces, and by them is hurled against another surface coated with material whose atoms will release electrons readily. Each electron is bounced so forcibly against the atoms of this surface that on the average it knocks out five more electrons. These secondary electrons are then in turn hurled against another sensitive surface, from which each produces its further quota of freed electrons. The same procedure can be repeated as many as a dozen times in a single tube, with the result that each electron initially set free by the light at one end of the tube may cause a hundred million electrons to be freed at the other end. Such a tube opens great possibilities in television, for with its aid

the "electric eye" can be made far more sensitive than formerly, and glaring lamps are no longer necessary to illuminate scenes which are to be broadcast.

Still greater advantage will result if the electron-multiplier principle can be applied to amplifier tubes in which electrons are released from a hot filament. This is impossible at present because the sensitive coating on the plates which furnish the electrons would be destroyed by heat from the filament. Probably a material can be found which will give up its electrons readily, yet will be less affected by heat.

The cash earnings of the electrons which have been ransomed from matter have already run into billions of dollars; and in addition, putting electrons to work has put men to work. That four great new industries—the telephone, the radio, the phonograph, and the motion picture industries—rest directly on the vacuum tube and could not exist on so vast a scale without it, is usually ignored when new devices are blamed for technological unemployment.

When science set the electron free it took a great step forward toward freeing mankind from its yoke of want, hunger, and disease. The ransomed electron has already contributed in a thousand ways, and if the further opportunities it offers are properly utilized, will contribute in countless further ways to the comfort, safety, and security of human beings.

VII

SOUND BORROWS WINGS

I'll put a girdle round about the earth
In forty minutes.

A Midsummer Night's Dream

"FATHER, where is Somaliland?" came the voice from Junior's den, where an amateur radio transmitter filled one corner of the room.

"Somewhere on the east coast of Africa, I think." Ordinarily father would have supposed that tomorrow's geography lesson was being prepared, and that he was about to be required to bring back hazy memories of the location of the Straits of Bab-el-Mandeb or some similar recollection of grammar-school days. But the tone was too casual. "Why do you want to know?"

"Oh, I've just been carrying on a conversation with a fellow in Somaliland, and I wondered where he lived."

The world is now roughly divided into two classes of people—those who would accept the above (which actually occurred, by the way) as an obvious exaggeration, and those who would consider it a challenge. In the latter category are persons who happen to be possessors of short-wave radio receivers and are given to occasional listening on other wavebands than those reserved for broadcasting. Such a listener is likely to counter with a description of how he, that very morning, heard an aviator over Hong Kong asking for land-

ing directions, or a trans-Pacific plane requesting bearings.

Before our appreciation of the achievements of radio has been dulled completely by familiarity, it is worth recalling the discoveries which have made it possible for an American boy to carry on an incidental two-way conversation with a British lad half the world away, through the effortless direction of a beam of energy carrying less power than is required to operate an automobile headlight.

During the coronation ceremonies of King George VI, an early morning walk of a few miles through the streets of any city in eastern America would have sufficed to convince a skeptic that a wide audience listens to radio broadcasts of events of great interest. Block after block, from one group of homes and then from another, came the droning voice of the Archbishop of Canterbury. Truly no archbishop before, whether he spoke with the tongues of men or of angels, had such opportunities of sound production. Every tiny breath of air rushing past the archiepiscopal vocal cords was caught up and repeated in a responsive chorus by more than forty million inanimate voices throughout the world. And the stroller, catching the Archbishop's words filtering through windows three thousand miles from Westminster Abbey, nevertheless heard them sooner than did persons at the far end of the building in which the words originated; for the sounds of his voice traveled through the air only about 1100 feet in a second, while during that time radio waves could carry them around the world seven times.

Radio-telephony, in its most modern use of broadcasting entertainment, is one of a few scientific advances which have been accepted by the world even more rapidly than they could be developed satisfactorily to meet the demand. In 1921 radio burgeoned overnight into a new industry which

within fifteen years came to rank in stature with the motion picture and automobile industries, and soon joined the telephone as the second industry dealing with sound waves to earn a gross income of more than a billion dollars a year.

In the United States, we have noted, there were in 1940 more than 37,000,000 radio receiving sets in operation, and 8,000,000 new sets were being sold annually. Throughout the world 25,000 registered stations were broadcasting news, entertainment, education, propaganda. That broadcasts of exceptional interest sometimes attract 50,000,000 listeners is well established, and, entirely apart from the wishful claims of advertisers, there is good evidence that leading comedians play to Sunday audiences of many millions.

Like any new toy in the hands of a precocious youngster with a large income, radio is being abused; and time is required to get its operation into equilibrium with the needs of society. Even twenty years after the inception of broadcasting, many radio receivers in homes were being kept in operation from morning to night, whether anyone was listening to them or not, and carefully obtained statistics showed that each of the 37,000,000 existing receivers in the United States was kept running more than four hours a day on the average. Quantity rather than quality was and still is the watchword, but the social need for the radio is very real nevertheless. Also, the rapid growth of broadcasting must not be allowed to overshadow the importance of radio in the fields of commerce, navigation, and aviation.

In an age and country which contain one radio receiver to each four members of the population, a special effort may be required to get into a suitable frame of mind properly to appreciate the magnitude of the accomplishments which were needed to make radio-telephony possible. Such an effort

might well involve imagining a bull-voiced orator of a previous century, who, seized with an overwhelming desire to send his voice into a neighboring county from his own front porch, learned by some divine revelation that he could perform this feat if he would apply himself to the problem. Should he take the obvious course of climbing a near-by hill each morning to carry out a series of exercises in voice projection designed to strengthen his lungs and increase his broadcasting power?

As a matter of fact, sound waves *have* been sent completely around the world under their own power, but to do this requires the efforts of a mountain rather than a man. The volcanic explosion of the island of Krakatoa in 1883 produced sound pulses which circled the earth at least three times, and this loudest sound in history lasted for several days, though after it had traveled 3000 miles its waves became so smooth that a barometer rather than a human ear was required to detect them. But sound waves in the air are at the mercy of every breeze, and any ordinary sound will be reflected and scattered by every tree and hillside, and so weakened by its own spreading as soon to be submerged in general atmospheric noise.

Since direct attempts at its solution must inevitably fail, the problem of transporting sound over long distances without wires had to be solved, like so many other human problems, by subtle indirection. If waves cannot be sent through one medium, transform them and send them through another medium, says the physicist. Thus, by using his standard trick of energy-conversion, he learned to transport speech and music almost any distance; and now conversation has been carried 3000 miles with waves containing energy sufficient to propel sound itself only half a block. The sound waves are first changed into equivalent electrical waves, as in the tele-

phone; these are then fastened to electromagnetic waves which will travel at high speed through space; then at the destination the sound is separated from the carrier waves and reclaimed in its original form. In this way a laugh or a song can be whisked through space like a fairy princess on a magic carpet, to arrive radiant and, barring static, with not a harmonic displaced.

2

As long ago as 1880 Alexander Graham Bell and other physicists developed a method of carrying sound without wires which operated on the principle of our modern radio, the sound waves being in fact transported on a beam of light. They called their device the photophone. But light travels only in straight lines, and since we live on a curving earth such ultra-short wave methods of radio had severe limitations and could be used over only short distances. Even if we could hope to send a beam of light around the globe by using mirrors, fogs and storms would still interfere. Longer and more penetrating waves were required to carry the signals; waves which would not be intimidated by interfering masses of matter, but would sail majestically through or around them.

In 1864 James Clark Maxwell, one of the greatest theoretical physicists who ever lived, was working in England on a theory of the electric and magnetic forces with which electrified particles attract and repel one another. Maxwell discovered mathematically that waves of an electromagnetic nature can exist in empty space, and that light and radiant heat are just such waves. Light and heat waves were known to be extremely short from one crest to the next, but Maxwell decided that longer waves of a similar nature might also exist.

Actually every lightning flash in the heavens had been radiating such waves in abundance since the beginning of time, but no one was aware of this, and so far as mankind was concerned Maxwell's long waves remained only predictions for more than twenty years.

In 1887 Professor Heinrich Hertz, a young German physicist, was in his laboratory making miniature flashes of lightning jump between two metal balls by means of a spark coil. He chanced to notice that occasionally another spark would jump across a narrow gap between two ends of a loop of wire which was not connected to his apparatus. He quickly investigated the cause of this extra spark, and soon found that rays sent through space from the first spark were producing the second. He rightly concluded that these were the electromagnetic waves which Maxwell had predicted, and Hertzian waves were thus given to the world. Essentially the same as light waves, they differ in being longer and in vibrating more slowly. A ray of light will endeavor to shake any electron it may strike from side to side more than 100 trillion times in a second, while these more leisurely waves will shake it only a few million times. Their greater length enables the Hertzian waves to pass through such minor bits of matter as trees and wooden buildings, and waves still longer than these can cross mountains and seas like giants in sèven-league boots.

The world of physics was set into great excitement by Hertz's discovery, and soon his experiments were being repeated and extended in a dozen laboratories. At the University of Bologna, Professor A. Righi demonstrated the waves before his classes in physics, and in one of these classes was an eighteen-year-old student named Guglielmo Marconi.

Marconi's imagination was fired. Why shouldn't such waves be harnessed to carry signals across space? Why

shouldn't he be the one to try this? He applied himself with renewed diligence to learning all that was then known about the theory of electric waves, and by the time he was twenty-one, in 1895, he was ready to start experimenting.

Marconi set sparks to jumping between two metal balls connected to electrical condensers and loops of wire, as Hertz had done, but soon found that the radiated waves could be detected at greater distances if he held farther apart the two metal plates which formed one of the condensers. He raised one plate higher and higher, and lowered the other until finally it rested on the ground, which seemed to make matters better. Soon he had substituted for the upper plate a network of wires hanging between two masts, and for the lower plate the ground itself. Whenever he was able to double the height of the masts which held up his network of wires, he found that the distance at which the waves could be detected increased four times; so eventually he had raised these aerial wires 800 feet above the earth. Thus did Marconi discover the principle of the antenna or radio aerial, and learned that to launch waves properly into the ether he must have the antenna grip this ether as broadly as possible. Electrical oscillations were produced by the spark, and these, surging up and down the wire of the antenna, set a section of ether to quivering, from which electromagnetic ripples spread out through space.

Marconi soon found that he required a more sensitive detector of the waves than Hertz had used, and for this purpose he adopted the coherer, a device well known at the time in physical laboratories, which permitted a current to flow through a telephone receiver whenever incoming waves set up a surging of electrons in the receiving antenna to which it was connected. In the telephone the dots and dashes of the

telegraph code could be heard, produced by interrupting with a telegraph key the spark which set up oscillations in the transmitting antenna. There was no need to furnish any sound for the waves to carry, since the spark produced both sound waves and electric oscillations at the same time.

Within a year Marconi was able to send signals across space for two miles; by the end of 1897 he had pushed them 18 miles, and in 1899, with a very high antenna, signals were sent 85 miles across the English Channel. It appeared probable that to send the signals farther would require impracticable amounts of power, and that the curvature of the earth would require use of impossibly tall masts, but both of these difficulties turned out to be non-existent. Marconi's genius lay to a remarkable degree in refusing to be deterred by difficulties that had not yet been proved.

Soon, instead of further increasing the power of the waves sent out by his transmitter, Marconi turned to making his receiver more sensitive in detecting the signals after their attenuating trip through space. He had to work without amplifiers of any kind, and was handicapped a million-fold in available sensitivity compared to those who use our modern methods. But Sir Oliver Lodge had previously discovered how to tune electrical circuits to resonate with each other, much as a pair of connected pendulums adjusted to a common rate will affect each other much more than if not so adjusted; and Marconi made use of Lodge's method to improve his circuits. When a receiver was tuned to resonance with a given transmitter, not only would it respond more readily to the signals from this, and hence make them louder, but when several transmitters were operating simultaneously a receiver would respond only to that transmitter which sent waves vibrating at exactly the proper frequency to build up current surges in its circuit.

In 1901, on his first attempt, Marconi spanned the Atlantic Ocean with three faint audible dots, repeated over and over, and the world soon awoke to the possibilities of signaling without wires. The waves *would* curve around the earth, instead of being lost in space by following a straight path! Marconi was twenty-seven. Eight years later he was awarded the Nobel Prize in physics.

Marconi's experiments showed that electromagnetic waves could be used to carry sounds over great distances, but the sounds he used were of necessity the harshly sibilant tones of an electric spark. For radio-telephony some method of producing electrical oscillations of smooth and even character, without built-in sounds, was needed. Methods of producing quiet electrical oscillations were soon developed independently by several physicists, and in 1906 Reginald Fessenden applied such undamped oscillations to an antenna, arranged a microphone to incorporate any desired sound into the structure of the waves radiated, and sent his voice and a record or two out over the ether, to the startled enthusiasm of a few ships' radio operators who happened to be listening, even in those early days.

Still the radio-telephone lacked the final element to make it practical for broadcasting purposes—the three-electrode vacuum tube. Not until 1912 did de Forest really get his tubes to amplifying weak currents properly, and in that same year he found that the tubes could also be used to produce smooth oscillations, and thus could produce the waves as well as detect and amplify them. Since that day the electron tube has become the most important device in radio and is now used for no less than six entirely separate functions in transmitters and receivers.

Before 1918 the principal uses of radio were for communica-

tion between ships and across the Atlantic Ocean, and for trans-etheric chatter among more than five thousand licensed amateur operators in the United States who were interested in radio as a hobby. When World War I ended, thousands of young men who had been trained in radio were returned to civil life, and hundreds of new amateur licenses were issued each week. Then in 1920 a musical program which was informally but regularly transmitted from a Pittsburgh radio station attracted increasing numbers of listeners, and soon radio broadcasting swept the land and the world. By 1927 there were 733 broadcasting stations in the United States alone.

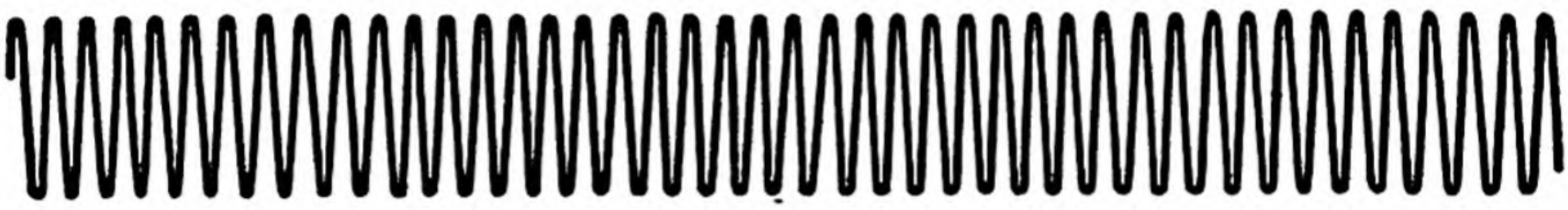
¶ 3

In a broadcasting studio the sounds which it is desired to send into space are produced in front of a microphone, or electric ear, which thereupon creates an electrical replica of their wave form. This replica, carried by a constantly varying current of electrons, is amplified with vacuum tubes and is then sent to another tube, called a modulator, which, like a tailor cutting cloth to a pattern, molds electrical oscillations of high frequency to the form of the sound replica. Though the process by which an electrical replica of a sound vibration can be attached to other vibrations is somewhat difficult to visualize, the result is shown in the curves on page 140, which are traces of the two kinds of vibrations, apart and together. To distinguish between them the vibrations of low frequency, which result from the sound, are called audio oscillations; those of high frequency, which are to produce the radio waves, are called radio oscillations.

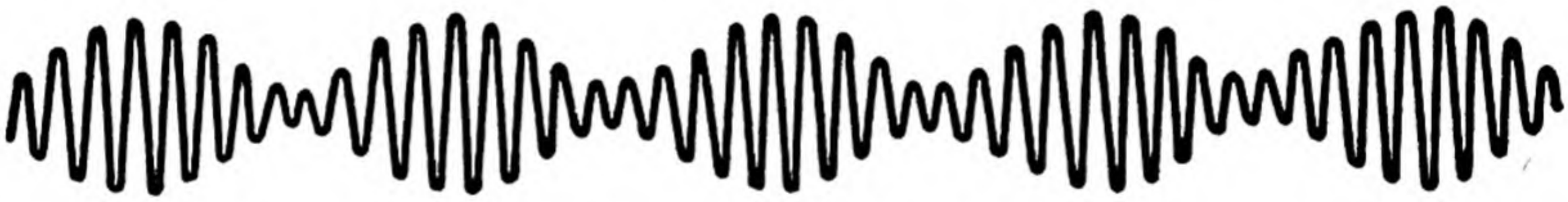
The radio oscillations are produced by a large vacuum tube

which has been put into a state of chronic electrical jitters. The frequency of the oscillations can be controlled by adjusting condensers and coils in connection with the tube. When the oscillations have been molded by the sound replica

A sound wave produces audio oscillations of low frequency.



A radio oscillator produces radio oscillations of much higher frequency—here only several times as rapid, but actually a thousand times more rapid.



When the audio wave is attached to the radio wave by modulating it, the resulting vibrations appear somewhat like this.

they are sent into the antenna, which then launches corresponding electromagnetic waves into space.

The radio waves used for ordinary broadcasting are so long that a skyscraper will interfere with their passage no more than a matchstick impedes the passage of ripples on water. As the waves proceed through space their amplitude grows continually less, but their length between successive crests, and the rate at which they vibrate, remain exactly constant. All radio waves travel with the speed of light (186,000 miles a second), and the number of times a wave will vibrate

in a second can be determined by dividing its wavelength into this velocity. A typical wave used in broadcasting is one-fifth of a mile long; and such a wave oscillates about a million times in a second.

An important station may radiate a hundred kilowatts of power in the form of ether waves. By the time this energy has spread over the earth so as to reach receivers a thousand miles away, less than one-billionth of it comes within the grasp of any single antenna. The term broadcasting is very descriptive, for in no other process does man spread energy so widely over space.

When the waves strike any metallic object they seize on the electrons in this which are free to move, and set them to surging back and forth as the various parts of the wave pass across them. A receiving antenna is such an object, so disposed that the waves will produce the maximum surge of electrons in it; these surging currents are then amplified in the receiving set until the signals they carry can be detected.

The electronic surges which the incoming waves produce can be greatly increased if the wave impulses are timed to occur exactly with the interval required for the electrons to be swished from one end of the antenna to the other; and this interval can be adjusted by tuning or adjusting the electrical vibration rate of the antenna or an electrical circuit associated with it. As a violin string has a natural frequency of vibration when plucked mechanically, so any electrical circuit has a natural frequency at which it will oscillate when struck electrically. To change this vibration frequency, radio receivers are provided with a control by which the electrical capacity of a condenser in the circuit can be adjusted, an operation analogous to turning the peg on a violin to change the tension on a string.

The actual amount of energy picked up by a receiving antenna is incredibly minute, but vacuum-tube amplifiers are able to coddle any faint incoming wave and bring it up to the level of human perceptivity, so long as it is stronger than the background of electrical noises which disturbances in the atmosphere constantly provide. Man himself produces much artificial static with his numerous modern appliances, for anything electrical which is turned on and off rapidly is a fruitful source of oscillations which are sent back into the power lines, and these can then radiate waves in profusion. An electrical machine in Cambridge, Massachusetts, was in fact at one time found to be the origin of noises which were greatly interfering with radio reception in Philadelphia. The actual power picked up by a receiving antenna may be a thousand times less than that with which a breeze shakes a leaf, so it is not surprising that such weak signals are easily overwhelmed. But a signal strong enough to remain above the level of background noise can be amplified a billion times in intensity, if necessary, until it is enabled to produce audible sound from a loud-speaker.

In the early days of radio, when receivers were relatively coarse and insensitive and little amplification was possible, receiving antennas were of necessity high and far-reaching, to insure a wide embrace to any incoming ether waves. As receivers have improved in sensitivity, the antenna has become less important. A big aerial may do more harm than good when near streetcar lines or other sources of electrical interference, since it may pick up as much extra static as increased signal, and much more interference from close at hand than would be intercepted by a small aerial.

The currents produced by the incoming waves in the tuned receiver are first amplified with vacuum tubes and then sent

into a special tube called a detector, whose function is to strip the load of audio vibrations from the carrier vibrations and cast the latter aside. Next the audio vibrations are further amplified, are subjected to various refurbishing processes (which are discussed in a later section), and are then fed to the loud-speaker which is to transform them back to sound.

An important development of broadcasting after 1930 was the rapid growth of chain networks, groups of transmitting stations fed with sound from one or more central studios by special telephone lines. One large network had a telephone bill for leased wires of over $3,000,000 during one recent year. The telephone equipment—microphones and amplifiers and transmission lines—must be specially designed for tone quality and volume range, since it is required to pass vibrations of from 30 to 5000 cycles per second at least, instead of the limited range handled by the ordinary telephone. Chain broadcasting will doubtless be greatly extended in future, since high-quality programs can thus be more widely disseminated and the speech and music, being exposed to static and interference over only short distances, pick up less noise.

([4

THE ELECTRICAL OSCILLATIONS most conveniently produced with types of apparatus which are readily available are those vibrating from 15,000 to 1,500,000 times a second—15 to 1500 kilocycles. (One million cycles is one thousand kilocycles or one megacycle.) Such oscillations radiate waves which vary in length from 20,000 meters to 200 meters, the more rapid oscillations producing the shorter waves. Early experiments showed that long waves would carry signals farther with a

given amount of power than would short, so the longest practicable waves, stretching more than twelve miles from crest to crest, were assigned to transatlantic stations. Since no commercial station wanted to use the easily daunted 200 meter waves, they were assigned to the amateur radio enthusiasts. The amateurs were not particularly pleased at being given the tag-end of the electromagnetic spectrum, but this assignment was to result in a remarkable discovery. Some amateur operators, making tests with waves even shorter than the assigned 200 meters, began to hear one another clearly over astonishing distances. Before long they were conversing easily, though thousands of miles apart, by using amounts of energy which would serve to send long-wave signals only a few miles. The short waves were found to be less dependable than long waves, and signals sent with them often became temporarily inaudible, but their occasional penetration of vast distances suggested important possibilities.

The reasons for the fading and the great range of the short waves soon became obvious. A radio antenna, it was found, emits two sets of waves: a sky-wave which travels off into space, and a ground-wave which keeps one end attached to earth like a trailing finger, and so is led around the bulging contours of the globe. When waves longer than 200 meters were produced the ground wave was being used, for the sky-wave traveled straight out into space and much of it was lost. But, strangest and luckiest bit of providential co-operation, nature was found to have arranged a set of radio mirrors high up in the air, from fifty to two hundred miles above the ground, extending all the way around the earth. These mirrors reflect back to earth sky-waves shorter than about 100 meters, though to longer waves they are transparent.

The existence above the earth of electrically charged layers

of gas in which are great numbers of ions, produced when electrons are knocked out of the molecules which compose the atmosphere, was suggested independently by Arthur E. Kennelly and Oliver Heaviside. It became evident that these Kennelly-Heaviside layers, extending as hollow globes around the earth, were the mirrors which reflected the radio waves. Some of these layers of ions are now known to be produced by ultra-violet light from the sun, which explains why they change markedly between day and night, while in others the ionization is produced by electrons shot from the solar disk. Thus the close connection between sunspots and radio is explained, for, when the sun shows great numbers of spots on its face, the number of particles which it shoots out is increased, and the ionized reflecting layers in the earth's atmosphere are greatly strengthened.

Particularly effective radio-mirrors are found 65, 130, and 190 miles above the ground. At times the density of ions in these layers becomes too low for good reflecting, and they allow the signals which strike them to escape into space. Music coming clearly at one moment from across the world may then fade completely away, to reappear a few seconds later, as the hole which has developed in the heavenly reflector is closed up. The reflecting layers change their positions and densities between day and night and with the seasons, so each short-wave radio broadcasting station is usually assigned several wavelengths, that it may be equipped to use waves to fit the reflecting layers which happen to be available.

Fading of signals is one of the greatest limitations of short-wave radio, and how much can be done to eliminate it in home receiving sets is questionable. But much can and is being done by large commercial laboratories, which receive short-wave overseas broadcasts and then re-broadcast them

over chain networks. Several systems for reducing fading have been devised; one will serve for illustration. Three separate, widely spaced antennas are used to pick up the same signals from different directions in space. The signals from all three are then sent to a common receiver, which puts them together into one signal whose intensity is governed by that from the antenna which happens to be providing the loudest signal at the moment. Usually, fading occurs in only one or two of the antennas at a time, one at least always giving a strong output. The signal strength is thus kept almost uniform, and fading is reduced to less than one-tenth its ordinary value. Though effective, such installations are too expensive to be used except where speech and music from them are to be distributed to thousands of listeners.

Static, the major curse of radio communication, comes mostly from thunderstorms. A good strong flash of lightning may discharge 250,000 amperes from cloud to earth, and can thus set half the antennas in the world vibrating, no matter how they may be tuned. There is, however, less static in the short-wave part of the radio spectrum than at longer wavelengths. The best way of overcoming static is to send out far more power than the worst current thunderstorm, but this method has obvious limitations. Arranging the sending antenna to focus its waves in the desired direction, as a searchlight focuses its beam, is helpful, and this can be done very effectively with short waves. Also the receiving antenna can be focused so that it will preferentially pick up waves from a given direction, and thus interference from unwanted signals not originating along the line connecting transmitter and receiver, whether from human or celestial broadcasters, is reduced.

Perhaps even more important than the traveling ability of

the short radio waves, which range from 100 to 10 meters in length (3 to 30 megacycles in frequency) is the fact that when they are used, more broadcasting stations can launch signals into a given area without mutual interference. To reproduce sounds with even moderate fidelity requires that vibrations of from 60 to 5000 cycles be carried, and this vibration load sticks out from the carrier wave like a barn door carried on a bicycle. If a station which is broadcasting on 300,000 cycles transmits sound waves containing 5000 cycle vibrations, its signals will overlap those from a station broadcasting on 305,000 cycles or 295,000 cycles, and a gap of at least 10 kilocycles must be left between frequency assignments of broadcasting stations which might interfere. The necessity for this is shown by the "monkey-chatter" which comes from sensitive receivers when two stations interfere. In the standard broadcasting range of 550 to 1500 kilocycles, there is room for only 96 channels each 10 kilocycles wide; more are needed. The higher the carrier frequency the narrower, relatively, is a band width of 10 kilocycles, so hope of increasing the number of available channels lies in the short-wave bands.

5

MANY RADIO MANUFACTURERS are frankly disillusioned about improving the quality of sound reproduced from their radio receivers. Sets of high tone quality are being made, but most radio buyers, it is said, either cannot afford or do not want faithful reproduction of fine music, preferring merely sounds which can be used as a background to living. Since the high tones of speech and music interfere with conversation, and since in many households the radio is kept operating from

morning to night, loud-speakers which produce mainly a low "boom, boom" in the background are preferred to those which faithfully reproduce the original music. In the trade jargon, the public has "tin ears."

Such limitations arise, of course, from the rawness of a new and rapidly growing art form, and will tend to disappear in time. The proportion of high-fidelity radio receivers sold is increasing annually, and the quality of broadcast programs improves as public taste educates itself. On the economic side science has taken a hand, for a far better radio receiver can now be bought for twenty dollars than four hundred dollars would buy in 1920, and a few dollars extra will make it serve as an excellent phonograph. Three hundred dollars will now buy 90 per cent of all that anyone could ask for in a radio, but the lacking 10 per cent is very expensive, and not all of it is yet, in fact, entirely attainable.

Some of the reduction in receiver cost has resulted from mass production methods of manufacture, for whereas annual radio sales in the United States were in 1921 only $9,000,000, by the beginning of World War II they had grown to more than $500,000,000. But much more of the improvement has arisen from more effective electric circuits, from better vacuum tubes and new ways of using them, and from the research on sound and electrical waves which produced such great improvements in the telephone and the phonograph.

A radio receiver, in addition to being a musical instrument, is also unfortunately a piece of furniture and a complex scientific gadget. As a musical instrument it finds its response limited at high frequencies by station-crowding in the wavelength bands, which at present sets a legal upper limit of 5000 cycles, while furniture fashion cuts off the low frequencies by preventing the use of a suitable loud-speaker. Yet

much has been done to reduce the effect of these limitations. and receivers have been simplified mechanically by making them more complex electrically, so that now a small box of coils and condensers and vacuum tubes is made to control its own sensitivity, its tone quality, and its range of volume. and even to tune itself automatically.

One limitation of ordinary receivers is that by popular demand they attempt to fulfill every radio possibility, and hence do nothing really well. Ninety per cent of all radio listening is to stations not more than 100 miles away, and the requirements for a set suited to these conditions are very different from those of one which is to respond with sensitivity and selectivity to many distant stations. Two stations broadcasting on close-lying frequencies can be separated only by using a receiver of high selectivity, one which can be sharply tuned to respond to only a narrow frequency band. But this operation of itself mars tone quality, for if music is to be reproduced with even average quality the set must be tuned to a band at least 10,000 cycles wide. Therefore high quality receivers are provided with controls which can be adjusted to make them either highly selective, or faithfully responsive to the entire tonal range.

Automatic control of sound volume gives an example of how a stream of electrons can be made to achieve a surprising result in a very simple manner. Every radio receiver is provided with a knob for adjusting the flow of current to the loud-speaker, which knob controls the output of sound as a faucet controls the output of water from a pipe. But such control is not enough, for a near-by powerful station will produce a torrent of sound, while faint signals from a weak station, or one far away, need greater amplification, and tuning a set would thus require constant adjustment of volume.

Automatic volume control makes the sound from all stations almost equally loud by constantly varying the sensitivity of the set to give a uniform response to electromagnetic waves of any intensity. Unfortunately the receiver cannot distinguish between wanted and unwanted signals, so it may amplify atmospheric cracklings and bangings unduly when it can find no signals to amplify, as when shifting stations.

The volume of sound produced is controlled automatically by detouring some of the electrons which come from one of the amplifier tubes, and sending them back to control the sensitivity of an earlier tube. If the output tube sends back more than the normal number of electrons, these partially anesthetize the set and cut down its sensitivity. Conversely, if the output current is unusually weak, less current is sent back and the early tubes are allowed to exert themselves to produce maximum sensitivity. The action is similar to that of a steam engine governor, in which the speed of revolution of a pair of balls is made to adjust the throttle to give a constant engine speed, no matter how much power comes from steam in the boiler. The human eye behaves similarly, its control nerves being so adjusted that when the light grows dim, its pupil opens wider.

Automatic volume control has made the tuning of a radio receiver less definite, for whereas previously a set was known to be correctly tuned when the sound output was at maximum, now the output level is merely that determined by the hand volume control. The difference between a carefully tuned and a poorly tuned set can then only be judged by the quality of the sound received, and quality, especially that produced by some modern band instruments, is less easily judged than volume. Tuning by eye has therefore been introduced to supplement tuning by ear, with small cathode ray tubes—

called "magic eyes"—being arranged to blink (i.e., to narrow a beam of electrons striking a fluorescent screen) when tuning is exact.

A further development is push-button tuning. Just as a steel ball, if dropped into an egg cup, will roll into the exact center of the cup, so a receiving circuit can be arranged to pull itself into exact synchronism with an incoming oscillation. Someone must of course decide which of a whole row of egg cups the ball is to be dropped into, so an electric motor is arranged to bring the set roughly into tune with any desired station when the proper button is pressed, and the set then pulls itself into exact synchronization. To reduce noise from static while changing stations, the amplifier response is automatically deadened until the set is correctly tuned.

Sound can be compressed for shipment just as hay is baled; wherefore many radio receivers are provided with means for automatic expansion of volume. A symphony orchestra may produce sounds which cover a range in volume of 100,000,000 to 1. Such volumes cannot all be carried undistorted through telephone systems and amplifiers, or impressed on phonograph records, so the volume range is compressed. A sound which is really twice as loud as another may be transmitted as though it were only 1.2 times as loud, to take typical figures, and a sound of intensity 4, then, is given intensity 1.44; 8 becomes 1.73, and so on. In the receiving set much of the original volume can be restored, the circuit being arranged so that when it receives signals for a sound of intensity 1.73 it automatically produces 8. The amount of compression and subsequent expansion can be adjusted at will, entirely without moving parts except the facile electrons.

The volume range of the usual receiver is only about 1 to 1000, limited for soft tones by the hum coming from the

60-cycle alternating current which energizes the set, and in loudness by the rattling of the loud-speaker and distortion which marks overloading of the amplifier. This 1000-fold range in intensity is hardly sufficient, and in sets of high quality has been increased to 10,000.

¶ 6

THE TECHNICAL ASPECTS OF RADIO can be expected to improve considerably in the future. Improved amplifier tubes should decrease the internal complexity of high-quality receiving sets, and just as 3 vacuum tubes now perform feats which were difficult for 10 a decade ago, so our present 30-tube high-fidelity sets will probably be replaced by 6-tube sets in the future. Television has already markedly influenced the development of improved radio tubes, and can be expected to affect radio greatly.

Vacuum tubes of the types ordinarily purchased in stores cannot be expected to operate more than 2,000 hours, whereas the larger tubes used in transmitters, on which the demand is much greater, in some cases last as long as 20,000 hours in action. The difference is largely one of cost, and receiver tubes which will last for five years of constant use are obtainable if one will pay for them. Indeed, tubes can be made which will last for twenty years, and the possibility of making the tubes an integral built-in part of the receiver has been seriously considered. The objection to using inferior tubes arises not so much from the likelihood of their failing completely, since they can be replaced cheaply, as from a gradual decrease in their ability to evaporate electrons, so that the quality of

sound from a set in which they are used depreciates so slowly that its change is not noticed.

Static remains the chief bugaboo of radio, but it must be attacked by indirection, since it is composed of the same stuff as the desired signals themselves, and once mixed with them cannot be removed. The most promising methods of attack are chain broadcasting, directional sending and receiving, use of ultra-short waves, and "frequency modulation" or FM which appears particularly hopeful. Professor Edwin H. Armstrong of Columbia University developed this new system of radio transmission. The sounds to be carried by the radio waves are attached to these waves, not in such a way as to vary their amplitude, as is done in ordinary radio transmission, but in such a way as to vary their frequency of oscillation. This corresponds to singing a tone (the carrier wave) and then making it go up and down in pitch rather than making it louder and softer. The resulting freedom from static is paid for by a sacrifice in bands available for broadcasting; for many times the amplitude modulation (AM) band width is needed, so fewer broadcasting channels are available. For this reason stations which are now broadcasting with FM use very short waves.

An alternative to chain broadcasting, which will become increasingly useful as sound recording methods improve, is to record a program and send out several hundred records to as many stations, to be broadcast as desired. This insures that only a perfected version of the program will be used, which is desirable so long as human performers remain fallible. Many weekly broadcast features are now distributed by record instead of over wires, and the number of "electrically transcribed" programs can be expected to increase greatly.

Though broadcasting is that aspect of radio with which the public is most familiar, other applications are of equal or greater importance. Radio-telephony is especially important in aviation for automatic methods of communication, of direction-finding, and of blind-landing control. Police short-wave radio is having important results in the control of crime. Weather prediction is being facilitated by data obtained with balloons sent aloft to transmit by radio what they find in the upper reaches of the atmosphere.

Radio-telegraphy is still used for long-distance communication more than is radio-telephony, for the dots and dashes find their way through static more easily than do words, and a narrower channel of frequencies suffices for their transmission. Pictures are being sent by radio as well as by wire; and television, which requires a chapter of its own, will also be found utilizing these electromagnetic waves to which our eyes are blind, but for detection of which the physicist has provided an artificial sense.

VIII

EYES THAT SEE THROUGH ATOMS

That men may scan the record of each flame . . .

E. C. STEDMAN

THERE exist a few scientific instruments which, though they have contributed directly to the establishment of no vast new factories, and are never sold over the counter, are nevertheless of tremendous importance to science and industry, for without them many of the techniques which man has found most useful would not be available. One of the most powerful of these instruments is the spectroscope; indeed, Henry Norris Russell has called the spectroscope the Master Key of Science. It appears to be true that with this talented instrument scientists have succeeded in unlocking more secrets of nature than with any other single device. Though comparatively simple in its structure and operation, the spectroscope gives answers to an incredibly wide variety of questions merely by dissecting a beam of light and separating this into its component colors.

Is life possible on Mars? Ask the spectroscope. Is a certain painter's illness caused by lead poisoning? The spectroscope can tell. How much does the core of a helium atom weigh, and how much that distant star? Does this greenhouse contain the correct amount of carbon dioxide to support plant life? Of what is the tail of a comet made? How many electrons are there in an iron atom? Is this the sweater of the

burglar who crawled through that broken window? How hot is the sun? Thousands of such questions are being asked from time to time, and are being answered correctly with the aid of the spectroscope.

Any atom or molecule will emit light if it be struck a hard atomic blow, and all light originates from atoms which have thus been stimulated by heat or electricity. Since any material object—a star, a drop of blood, a speck of putty—is composed of atoms, any material object can be induced to emit light by heating it until it becomes an incandescent vapor. The light which is thus emitted carries inevitably in itself many secrets concerning the atoms from which it originated. It is the function of the spectroscope to analyze this light, and thus lay bare these secrets for the eye of science to read.

For fifty years physicists have been using spectroscopes to dissect atoms and to study their internal structures. By working out a sort of cross-word puzzle game, in which he uses, instead of letters and words, numbers representing various characteristics of the light which the atoms emit, the physicist is able to learn the positions of electrons in all varieties of atoms, to learn how the electrons jump about when atoms are emitting or absorbing light, and otherwise to get a very clear picture of the internal behavior of atoms. As this picture has grown clearer—and it is actually very clear, for despite accusations that the modern picture of the atom is now hazier than ever before, it is the atom which is hazier, not the picture—the physicist has been able to learn how to handle atoms more efficiently, and can tell scientists in other fields how better to handle them.

The chemist finds that a tiny pinch of salt needs more than a bathtub full of water in which to hide from the ferreting

eye of the spectroscope, and he uses this instrument regularly to detect and measure minute traces of impurities in the materials with which he works. So bright is the light which the atoms in a small speck of metal can emit, that a piece of brass the size of a pinhead will serve for a complete determination of the presence or absence of seventy of the chemical elements, and none will be overlooked which is present in an amount as great as one-millionth part of the whole. Indeed, at least ten of the chemical elements were originally discovered with the spectroscope.

Atoms which are to be studied with a spectroscope need not be anywhere near it, for the light which they emit can travel a billion miles across space and still deliver up its secrets when captured and analyzed. The astronomer is thus enabled to analyze the materials of distant stars, and has learned that even the farthest visible nebula is composed of the same atoms that we know on earth—dust similar to dust across the vast stretches of the cosmos. More than three-fourths of the discoveries of modern astronomy have been made with the spectroscope, and no large telescope is considered complete without one as an attachment to sort out the light it gathers. Nor is the spectroscope merely an analytical tool, for with it stars and nebulae can be weighed, their temperatures taken, their speeds through space measured, and the courses charted of their lives and deaths.

To the biologist and physician also the spectroscope is invaluable, for with it such complicated molecules as those of vitamines and hormones can be studied, and metallic poisons can be detected in the blood long before they accumulate in amounts sufficient to be harmful. If the human body is analyzed down to its constituent elements, almost every kind of atom is found, but many are present in extremely small

amounts. Which are essential to life and which are merely incidental? For example, little copper is found; too much copper is poisonous; yet some copper must be present if life is to continue. How much copper is too much, the spectroscope is helping the physician to determine. The same question must be answered for numerous other kinds of atoms.

Drugs also can be studied with the spectroscope. In cases where cocaine poisoning is suspected, a few drops of fluid taken from the spine of the patient can be diluted and the cocaine content can immediately be determined from its light absorption. To draw enough fluid for chemical analysis might harm the patient.

Engineers too find the spectroscope useful. With it they can look inside the cylinder of an engine while this is in operation, and study the burning and explosion of gases and the propagation of pressure in the cylinder. To do this a plug of metal is cut from the top of the engine and a thick window of clear fused quartz is inserted in its place. Through this window comes enough light to enable the user of a spectroscope to establish the temperature of the flame at any instant, and to give analyses of the composition and rate of burning of the fuel.

Even in crime detection the spectroscope is useful; it has had its day in court in a number of lawsuits. In one case, gasoline which exploded in a sewer was traced to one of a dozen filling stations in the neighborhood, from which it might have leaked, by using the spectroscope to show that the gasoline found remaining in the sewer absorbed light identically with the brand sold by the station. The "G-men" in their government laboratories use the spectroscope regularly, as do workers in the various state criminological laboratories, though not, however, with particular attention to what one

paper over-enthusiastically referred to as the "ultra-violent" region of the spectrum.

The spectroscope is thus at once a powerful tool for analyzing matter, a super-telescope, and a super-microscope; a super-speedometer, thermometer, tape-measure, and clock. In each role it exceeds in range and power the more common forms of these devices. This it can do because it attacks fundamentals; it studies the world and the heavens in terms of the very atoms of which they are made, and these atoms in terms of the energy which is their very life.

2

THE FOUNDATIONS OF SPECTROSCOPY were laid by a twenty-four-year-old boy. One day in 1666 a young student, later to win fame as Sir Isaac Newton, threw the first purposefully produced indoor "rainbow" on the wall of his bedroom. Newton thrust a prism into a beam of light which was shining through a round hole in his landlady's windowshade, and saw that the prism split the white light up into a bright spectrum of colors. By so doing he came breathtakingly close to inventing a spectroscope. If the sunlight had entered through a crack in the shade instead of through a hole, and if Newton had turned his prism so that its base was parallel to this crack, and had inserted a pair of lenses into the beam, he might have noticed dark streaks or lines running across some of the colors on the wall. More than a century elapsed, however, before Joseph von Fraunhofer designed a spectroscope which would separate light into its ultimate purity of color, and observed these dark lines in the spectrum.

Despite its tremendous analytical powers, a spectroscope

is really a simple instrument, and it has no moving parts to wear out. Light to be analyzed is sent into it through a narrow slit, and then passed through a prism or similar device which separates the different waves of light in accordance with their lengths. Waves of each particular length are sent in a particular direction, where they can be observed with a small telescope. The lenses in this telescope serve to heap similar waves neatly together in one pile, where they appear as a line of colored light, an image of the spectroscope slit in light of utmost purity.

If a neon sign or a mercury lamp be observed through a spectroscope, various sharp spectrum lines can be seen—red and green and blue and other colors—with dark spaces between. If light from an incandescent lamp be so analyzed, a complete spectrum is seen, for hot filaments emit light waves of all lengths in the visible range; and the numerous lines, packed infinitely closely, merge together to form a continuous band of color.

The great power of the spectroscope arises from the fact that under sufficient provocation all atoms and molecules emit light, and each of the kinds of atoms which make up our earth—iron and hydrogen and sodium and more than fourscore others—emits light of certain wavelengths and those only. Since light waves are identical with ultra-short radio waves, under proper stimulation every atom becomes in fact a tiny short-wave radio transmitting station. When a radio set is tuned to a certain wavelength, a peak of sound intensity is heard if some station is broadcasting on that wavelength; a spectrum line is a peak of light seen at a certain wavelength because an atom is broadcasting on that wavelength. The millions of atoms in a flame or electric arc broadcast on hundreds of frequencies at the same time, but the

spectroscope can be tuned to all these wavelengths simultaneously, sorting them out so that all can be observed together without mutual interference.

Though the waves which the atoms emit bring no purposeful message, they tell much; and by literally reading between the lines (to seven figures, in fact), the physicist has been able to deduce many particulars about the atomic world from the broadcasts which originate there. Most important is the identification of sending atoms merely by noting the wavelengths on which broadcasting is being done. Just as an experienced radio listener knows that he is hearing station WZZZ when he turns the radio dial to 422 meters and hears any sort of noise, merely because WZZZ is the only station which broadcasts on that wavelength which his set will pick up, so a spectroscopist knows that he is looking at light from sodium atoms when he sees the familiar yellow light of the sodium flame, because sodium atoms broadcast on the yellow wavelength 0.5893 micro-meters. (This is usually written by the spectroscopist 5893 Angstroms; ten billion Angstroms is almost exactly one meter.)

The spectroscopist can be even surer of his station identification than the radio listener can, for each atom broadcasts not on one wavelength only, but on a whole group of wavelengths. Iron atoms, for example, when made sufficiently hot are found to produce more than 20,000 spectrum lines. All told, more than a million separate spectrum lines have been distinguished; and most of these have been identified as caused by light which has come from one or another of the various kinds of atoms and molecules of which matter is composed. Since one or two carefully measured lines will serve to identify the atom which emitted them, it thus be-

comes almost impossible for an atom to mask its identity if its light can be sent through a spectroscope.

The patterning of lines in a spectrum is a language which the spectroscopist has gradually learned to read clearly. As the series of irregular black marks on this page conveys certain ideas to a reader, so the unevenly spaced lines in a spectrum convey to the scientist flashes of information—here is iron, here arsenic, here are lines of copper and lead. Some of the lines are brighter than others, so the light can even be made to tell how many atoms of each kind are broadcasting—here is a great deal of iron, here a little arsenic, here too much copper in this lead.

Since the spectroscope arranges the spectrum lines in order of wavelength, it is not necessary that they be seen in color, and they can therefore be photographed and later identified from their positions on the resulting spectrogram. This method of observing spectra is now commonly used, both because the records thus produced can be studied at leisure, and because many spectrum lines are found in the ultra-violet and infra-red regions where they cannot be seen but can be photographed with ease. When a camera is thus used in combination with a spectroscope, the resulting instrument is called a spectrograph.

Most small spectrographs contain a prism to split the light which passes through them into its constituent wavelengths, but large instruments use a more powerful device, a scientific light-sieve called the diffraction grating. This is usually a highly polished mirror on which as many as 200,000 sharp parallel scratches have been accurately ruled with the point of a diamond. These narrow scratches, when evenly spaced twenty or thirty thousand to the inch and accurately placed to within a thousandth of the thickness of a hair, sort the

light waves into spectrum lines without the use of auxiliary lenses. Prisms must be made of transparent material; glass serves for visible light, but quartz is needed for ultra-violet, and rocksalt or some similar material for infra-red light. A diffraction grating ruled on a mirror has the advantage that, within reason, it can be used with waves of any length.

A large diffraction-grating spectrograph requires a vast, vibration-free room to house it, and can throw light into a spectrum stretching a hundred feet around a huge circle. Such instruments are giants compared to the most common spectroscopes, small brass tubes on tripods familiar in elementary science laboratories. The positions of spectrum lines can be determined to within 1/25,000 of an inch, and when such precision is attained the length of the light waves is determined to one part in three million. Since the light waves are themselves only about 1/50,000 of an inch long, their lengths can thus be found to within a few trillionths of an inch—a billionth of the thickness of a hair.

3

When a spectrograph is used to determine which kinds of atoms are present in a given sample of material, the sample is vaporized and a discharge of electric current is sent through it. The simplest method of accomplishing this is to strike an electric arc between two pieces of very pure graphite, and insert into this arc the speck of metal or clot of blood which is to be analyzed, so that it is burned to nothingness. This burning tears the molecules of the material apart, separates them into their constituent atoms, and pounds each atom so

hard with a deluge of electrons and other atoms that it emits the light which reveals its identity.

Suppose that a manufacturer of watches finds that a competitor is using a new hairspring of remarkable quality. This spring must be duplicated or improved on at any cost, but what can it contain that confers on its steel the new temper and elasticity which are so desirable? If a chemist is to analyze the spring by ordinary means he must buy several dozen watches, extract their tiny springs, and then guess which substances are most likely to be involved, so as to select the proper chemical reactions to carry out. He must dissolve and mix and scrape and weigh his materials with the greatest of care, for one single atom of a new alloying material to every 100,000 atoms of the watch-spring material may be responsible for conferring the high quality, and these are easily lost in a tiny sample.

How much more directly can the problem be attacked with a spectrograph! Now the chemist need merely strike an electric arc between two pieces of graphite, insert a small section of the spring into the flame, and let the flash of light which results enter his instrument and be recorded. When the plate is developed it shows hundreds of spectrum lines, and from these can be selected those which are known to arise from each kind of atom. It is but the work of a few moments to identify lines of iron, copper, chromium, nickel—all common in springs of one sort or another. But here are some lines which belong to beryllium—there must be beryllium in the spring! That no metallurgist or chemist would have guessed that beryllium would improve a hairspring is of no consequence, for the beryllium is there, it is the only new element present, and the springs are strong and supple.

Almost any material can be burned in the blistering 7000°

F of an electric arc, and if a material can be burned its metallic constituents can be determined with the spectrograph, whether it be a sample of blood from a patient suffering from lead poisoning, a drop of condensed milk thought to contain more than one part of copper in three million parts of milk, or paint from an automobile suspected of having collided with a lamp post. Since it is not necessary to know in advance what kinds of atoms are being looked for, almost every kind of atom can be tested for in one operation.

No metal has ever been made so pure that the spectroscope could not find impurities in it. Even the superfine extra-pure 1000-proof gold which is the basis of the currencies of many countries is found to contain much atomic dirt under this revealing eye which sees through atoms; and if the average is like the samples which have thus far been measured at the National Bureau of Standards, dross of various kinds totaling more than a million dollars in supposed value exists in the gold of the world.

An entire freight train filled with pig-iron can be tested in a few hours by a spectroscopist dragging electric wires behind him as he proceeds from car to car, carrying a small spectroscope in his hand. Opening a car door he clips a wire to a sample pig, strikes an electric arc between this and a bar of pure iron he carries, and observes the light in the spectroscope. If certain impurity lines are fainter than a standard which his instrument shows, that pig contains sufficiently little impure metal, and he passes to another. By properly selecting samples at random the whole trainload of iron can be tested without bothering to unload it.

Amounts of metal so small as to be difficult to detect chemically are often of great biological importance. Why do the livers of scallops concentrate cadmium? Why do the irises

of the eyes of cattle more than three years old yield an ash which contains more than fifty per cent barium, a fact true of no other animal? According to the spectrograph, the red feathers of the touraco contain 7 per cent of copper, while the colored petals of flowers usually have a lower mineral content than do white specimens of the same species.

A little copper is good for the digestion, but too much is not. In areas where many cranberries are grown, sprays have for years been used to kill pests, and the Government at one time feared that the soil might have become so saturated with copper from these sprays that the cranberries might be absorbing more copper than would be good for their consumers. So cranberries, cranberry jelly, cranberry juice, dirt from cranberry bogs, and cranberry stems and leaves were all separately consumed in electric arcs and forced to reveal their copper content to the discerning spectrograph. Fortunately the instrument announced that all was well.

Very small amounts of lead or arsenic can do great damage to the human body, and lead poisoning is one of the greatest hazards of industry. Lead fumes are found in some mines, and in storage battery and paint factories. Unless some care is taken to protect workers in these industries the amount of lead in their bodies may slowly rise past the danger point, and once this point is passed the resulting diseases are very difficult to cure. It is therefore important to keep a constant check on the lead content of the blood of such workers. By placing a few drops of blood from a worker in a tiny carbon cup and striking an electric arc to this cup, the blood can be vaporized almost instantly, and any lead atoms present will emit their characteristic light, which can be identified with a spectrograph. This light being recorded on the photographic plate, a series of samples of blood containing no lead,

but with varying known amounts of lead added to each sample, is burned and has its spectra recorded. The spectroscopist matches the intensities of the lead lines in the worker's blood with those in some one of the samples whose lead content is known, and thus can measure amounts as little as one atom of lead to a million molecules of blood. If a person be allowed to sleep for one night in a freshly painted room, a definite, though harmless, increase in the lead content of his blood can often be observed with the spectrograph. Nor is this sensitivity confined only to lead, for any of the other sensitive chemical elements can be determined almost as readily.

That two or three parts of aluminum or lead can be detected in ten million parts of lobster or condensed milk may seem unimportant, since such concentrations are below the toxic limits considered dangerous to health. Yet obviously tests on the rapidity with which the internal coating of a can dissolves in foods stored within it can be made easily and quickly when such sensitive methods of detection are available.

Chocolate and chewing-gum manufacturers use spectroscopic analysis to insure that the lead content of their products is below the limit set by pure food laws. Has the arsenic and lead been properly removed from sprayed foods before canning? Is beer kept in cans dissolving anything more from the container than it would if kept in bottles? The spectroscope gives an easy, sure, and quick means of deciding.

So we find paper manufacturers who want to discover the source of tiny black specks in their spotless white product, producers of bakery equipment who wonder if their new coating compound for pans will contaminate the dough, spark-plug manufacturers who wish to study the effect of

minute amounts of alkali metals in improving sparking, all finding the spectroscope helpful.

Of recent application is the internal branding of manufactured products with hidden spectroscopic marks of identification. If you happen to be the manufacturer of a patented kind of chewing gum, and find that a firm in Mexico is constantly infringing your patents, but you cannot prove this in court because the Mexican gum is identical with yours and is put in similar wrappers, the spectroscope can help you. Just get a spectroscopist to determine all the kinds of atoms present in the gum, and then dump into your mixing vats a small quantity of some material containing two or three kinds of atoms not normally found in gum. Only a few grains of material will serve to brand a ton of gum, and this amount, though detectable spectroscopically, is so small as to affect neither the gum nor the chewer thereof. Then in future you can prove that a certain sample of gum which is said to be yours, but contains no tell-tale, is really the Mexican variety —at least until spectroscopes become more common in Mexico!

¶ 4

WHEN THE SPECTROSCOPIST burns a substance in an electric arc to force it to emit light, the molecules of which it is composed are torn asunder. These molecules consist, of course, merely of groups of atoms clinging together in definite patterns. When vitamins or hormones or other such complex materials are studied, it is the molecules themselves which are of interest, rather than their constituent atoms. Though such materials would be destroyed if burned, fortunately they can be studied with the spectroscope by an entirely different

method from the one used for detecting atoms—a method which leaves them entirely undamaged. If a material is at all transparent, light can be sent through it, and waves of certain lengths will be absorbed by its molecules. The spectrograph can then be used to obtain information about the molecules by analyzing not the light which it receives but that which is missing because absorbed before it enters the spectrograph.

Vitamin A, for example, has been found to absorb strongly any light waves which are slightly shorter than violet waves. Therefore, instead of feeding cod-liver oil to rats for weeks to discover how much vitamin A a given sample contains, the standard procedure now is merely to send a beam of ultra-violet light through the oil and measure with a spectrograph the amount of light of wavelength 3280 Angstroms which is absorbed by a layer of oil of measured thickness. Care must be taken to dissolve from the cod-liver oil any non-vitamin material which might absorb light waves of the same length; but such offending impurities can easily be eliminated from the oil by mixing it with chemicals which change them to soap.

Analyzing a translucent substance by studying the light it absorbs is particularly convenient because the material is not destroyed, and the method is quick, clean, simple, and accurate. The two questions which any such analysis must answer are, "What substances are present?" and "How much is there of each?" Light-absorption measurements answer the second question definitely. It is estimated that a layer of material only five atoms thick can in many cases be detected by the light it absorbs. By combining a microscope with a spectroscope a speck of vanadium only 100 atoms long by 100 atoms broad by five atoms thick has been observed. Ability to detect such a clump of matter, containing only 50,000

atoms, weighing a billionth of a billionth as much as a dime, stamps this method as one of the most sensitive available.

All life ultimately depends on absorption of light, for it is the absorption of sunlight by the green leaves of plants which keeps the plant and animal worlds alive. Biologists have long used the spectroscope in their efforts to learn how the chlorophyll of green leaves manages to capture sunlight, and with its aid store in the leaf carbon from the air as cellulose, starch, and sugar. Many a leaf, green or brown or yellow, has been held before the slit of a spectrograph and had its inner structure plumbed with light in an effort to unravel the secrets of chlorophyll and carotin and other complex molecules on which life depends.

5

IN THE ULTRA-SHORT WAVE REGION OF THE SPECTRUM lies a broad band of waves entirely untouched except by the pioneering surveys of spectroscopists studying the spectrum for its own sake. Such useful applications of these waves as there may be—and there will probably be many—must wait until further experiments have been performed, experiments designed to perfect ways of handling these delicate rays. No one has yet succeeded in finding a solid material which is transparent to light waves shorter than one-fourth as long as those we call violet, and longer than X-rays, and which could be used for windows to allow light to enter and leave experimental apparatus. Thus far hydrogen and helium are the only materials which the ultra-short light waves have been found able to penetrate.

If, however, we pass in thought to the region of still shorter wavelengths—to electromagnetic waves less than one-thou-

sandth as long as those of visible light—we find ourselves again on familiar ground, for we have now reached the domain of the X-rays. X-rays require special kinds of spectroscopes for their study, but these have now been developed to a high state of perfection and are in everyday use to explore the hidden depths of matter.

Sir William Crookes might have discovered X-rays if he had been less efficient and more curious. One day, as Crookes was sending an electric current through a glass tube from which he had pumped most of the air, he noticed that a box of photographic plates left near the tube became fogged when the current was flowing, even though the box was not open. He found that the mysterious fogging could be cured by removing the wrapped plates from the room whenever the electric current was flowing. He was so interested in the tube itself that when he found how to cure the incidental fogging of the plates he concerned himself no further with its cause.

A few years later (1895) Professor Wilhelm Konrad Roentgen was doing similar experiments, puttering around with a high-voltage vacuum tube, and he, too, found that unopened boxes of plates were fogged when the tube was in operation. Fortunately Roentgen was not satisfied merely to protect his plates; he set out to find just why they became fogged. It did not take him long to learn that the fogging was produced when a mysterious green glow appeared in the tube, a glow which Crookes also had noticed. Roentgen soon found that a new type of ray, which he named the X-ray, was coming from the walls of the tube, and that it could pass through any box and paper in which the plates might be wrapped, and also through any books or even his hand inserted between the tube and the plates. Thus simply were these new rays discovered, rays soon to prove so great a boon

to humanity as a tool of both pure and applied science, and though destined to take dozens of lives, destined also to save millions.

The green glow which Crookes and Roentgen saw was light being emitted by the glass walls of the tube when electrons bounced against them. At the same time these electrons, or cathode rays, were stimulating the atoms of the glass to emit other waves of extremely short length, and these were the X-rays. Physicists have since found that X-rays are produced when electrons strike any atoms at high speed, and vice versa, that when X-rays strike atoms, electrons are hurled out.

An X-ray tube is a lamp designed to emit electromagnetic waves of extremely short length. Such tubes, seen in all hospitals and in many dentists' offices, consist of an evacuated bulb containing as perfect a vacuum as can conveniently be produced, and fitted with metal electrodes to which high voltage can be applied. Electrons released from a hot filament are pulled through the vacuum by the high voltage until they reach speeds of thousands of miles per second; at these dizzy velocities they are slammed against atoms of tungsten or some such heavy material, and as each electron strikes it splashes out a spurt of X-rays.

The higher the voltage applied to an X-ray tube the faster are electrons pulled through it; and the faster they move the shorter-waved and more penetrating are the X-rays produced. By using giant tubes which will stand millions of volts, X-rays can be produced which will go through several feet of concrete with ease.

The technique of handling X-rays is still very crude; we have no lenses to bend them, no mirrors to reflect them properly, no microscopes to see with them. In spite of these

lacks, two powerful methods of using X-rays have been discovered. The first is to take shadow pictures with them, such as have revolutionized medicine and surgery. The second is to send the X-rays through a special type of spectroscope which contains, instead of a diffraction grating, crystals of the material to be studied.

Shadow pictures show very little detail, but they show enough to locate an open safety pin in a child's throat, or a bullet hiding in a splintered bone. As they have become cheaper to produce and control, shadowgraph pictures are finding increased use in industry. Every box of candy sent out from at least one factory is X-rayed to forestall lawsuits brought by consumers who might bite on or swallow metallic foreign bodies. X-rays can be used to show whether eggs are good or bad; golf-balls are regularly X-rayed for symmetry of their centers, and airplane parts for worm holes and hidden knots. Metal castings can be inspected for internal flaws by the shadow-picture method, and high-pressure boilers and pipes are often X-rayed to insure that they contain no weak spots which might later cause explosions.

¶ 6

REVEALING AS IS THE GLIMPSE through flesh or metal which an X-ray shadow picture gives, it is crude compared to that obtained by means of an X-ray spectrograph. Then the glimpse is into the very atoms of matter themselves—even farther into the hearts of these atoms than is possible with an ordinary spectrograph.

In 1912 Dr. Max von Laue had the brilliant idea that a crystal, such as rocksalt or diamond, might separate X-rays

into beams of similar wavelength much as an ordinary diffraction grating separates light into its colors. The diffraction grating consists of thousands of parallel lines traced on a mirror; the crystal, argued von Laue, consists of millions of parallel lines of atoms, very close together, and perhaps these closely spaced lines are just what is needed to sort out the short-waved X-rays. Experiments carried out at von Laue's suggestion showed that his idea was a good one. When a narrow beam of X-rays was sent through a crystal, dark spots appeared on a photographic film held behind the crystal, and the positions of these spots were found to depend on the different wavelengths in the X-ray beam, and on the arrangements of the atoms in the crystal. Sir William Bragg and Professor W. L. Bragg soon were able to arrange the crystal in a spectrograph so that clear, sharp, spectrum lines, entirely similar to those produced when visible or ultra-violet light is sent through an ordinary spectrograph, were obtained with X-rays.

If X-rays are sent through a piece of metal, the small crystals of which the metal is composed can be studied with the X-ray spectrograph. This use of X-rays has particular application in the heat treatment of steel. In one foundry it had always been found necessary to keep certain metal parts for six hours in a furnace at high temperature in order to bring them to the desirable strength and hardness. The arrangement of crystals in the metal was studied, and the realignment of the atoms and crystals during heat treatment was watched with an X-ray spectroscope. As a result it became possible to work out theoretically a special short course of treatment lasting only half an hour. On trial this proved to give better results than the longer treatment, and at one-fifth the cost.

Pieces of metal which undergo great stress, such as airplane propellers, show changes in their internal structure some time before they are ready to break. Propellers are almost always X-rayed by the shadow method to discover internal flaws, but they should also be studied from time to time with the X-ray spectroscope to insure that their atoms show no signs of wanting to let go of each other.

Most up-to-date textile plants and metallurgical laboratories possess X-ray equipment. How well a piece of cloth will wear depends on the quality of the fibers of which it is woven, and how strong and flexible these fibers will be depends greatly on the character of the molecules of which they are composed. The X-ray spectroscope can be used to look right down through the fiber structure into the arrangements of atoms in these molecules; and sometimes it shows that improved arrangements of atoms would make better molecules, hence sturdier fibers, hence stronger cloth.

In cotton, wool, and asbestos fibers the molecules are found to consist of long strings of atoms lying side by side; here are substances respectively of vegetable, animal, and mineral origin which are similar in molecular and in outer form. Mica is composed of molecules which form broad flat crystalline plates arranged in layers which are held together so loosely that they can be split apart without difficulty. In diamond, on the other hand, carbon atoms hold strongly to each other in three dimensions to form crystals which cannot be torn or split, and hence produce the hardest substance known. But change the arrangement of these atoms ever so little and groups of them begin to slip apart, the crystal structure changes, and instead of the hard abrasive diamond, we have graphite, one of the most slippery solids known when wet.

If a piece of rubber is held between an X-ray tube and an X-ray spectrograph, the spectrum shows that so long as the rubber remains unstretched the molecules in it are arranged helter-skelter with no semblance of order. But when the rubber is stretched long chains of molecules appear, which contract and expand like coiled springs. The unusual ability of rubber to stretch and then return to its original shape can be traced directly to the molecules of which it is composed.

An important problem of an industrial age is lubrication. About this the X-ray spectroscope gives useful information, for it shows that greases and oils contain long molecules which slide over one another in layers, like eels which attach themselves to metal surfaces by their heads and then let their long bodies slither freely over one another.

The spectroscope is one of the instruments which is helping scientists to overcome the limitations resulting from the specialization which the increasing complexity of science makes inevitable. Workers in different fields find the understanding of each other's problems increasingly difficult, but mutual interest in a powerful tool does much to furnish common ground. Now astronomers, botanists, biologists, chemists, geologists, metallurgists, physicists, and workers in almost every other natural science and in many industries find their need of spectrographic methods helping them to a better understanding of mutual problems. Even more important, the spectrograph furnishes the only available means of solving many of these problems.

IX

THE DOCTOR AND THE PHYSICIST

Wisdom crieth without . . . Length of days is in her right hand.
Proverbs

THE wonders which medical workers have already brought about in the diagnosis and treatment of disease suggest that a time may come when the physician will be able to analyze most illnesses as soon as they start, and cure them before damage results. How soon this "golden age of healing" arrives will depend greatly on how close is the collaboration between research workers in medicine and those who work in the sciences on which medicine depends. The physician has long relied on the chemist for curative drugs, and on the physicist for diagnostic instruments and healing rays. In the one field new materials and in the other new devices are being produced in increasing numbers, helping to make imminent new miracles of medicine.

The X-ray and the microscope have extended the vision of the medical observer until he can see through ten inches of living flesh or into a single tissue cell, yet similar but much more powerful tools still await development. Modern electrical devices enable him to listen to faint murmurings of the life processes, or to measure feeble currents arising from heart and brain and nerve; yet electrical body measurements are but little understood. Now newly discovered atomic rays are being brought to help him destroy malignant invaders of the

human system, and there is every reason to believe that even more important curative rays await discovery.

Much of the aid which physics gives to medicine is of a deliberate sort: Here is a job to be done, says medicine; This is how to do it, says physics. But connections which are more striking can be traced between medical life-saving and some of the apparently impractical fundamental researches of the modern physicist. X-rays and radium, which have saved thousands of lives in the few years they have been available, are two early examples. Today, discoveries are being made which promise to be even more fruitful in their turn.

The X-ray, as we have seen, was stumbled on by Roentgen, a physicist, who had no inkling that the outcome of his experiments would prove so fruitful in relieving human suffering. Yet it would be incorrect to say that X-rays became available to mankind as the result of an accident. As well say that the sportsman landing a giant tarpon off the coast of Florida made his catch by accident because he could not predict in advance exactly what sort of fish he would hook. Most great experimental discoveries are made in a similar way. The accident, if such it must be called, is a planned accident, which could never occur if the scientist did not place himself in position for the lightning of discovery to strike.

Cancer now causes 135,000 deaths each year in the United States, but there is hope that eventually this number can be greatly reduced. During a recent year 76 per cent of the cancer patients in the principal hospitals in England were treated by radiation from X-ray tubes and from radium. The ray treatment would be far more effective than it is if only unhealthy cells were affected, but since to reach internal cancers the rays must first traverse normal tissue, where they produce

electron bullets which fly in all directions, an undesirable number of healthy cells may be killed. Rays are wanted which will be more penetrating.

Even if radium could always be used effectively there is not enough radium in the world to fill the present need. Only about two pounds—roughly $18,000,000 worth—is now available, and even this much radium, if gathered together and applied to one patient, would hardly be sufficient to treat some of the deep-seated malignancies which are found. Much comfort can therefore be derived from the knowledge that new super-giant X-ray tubes, and new atomic energy sources, can be designed to produce rays that will out-radiate radium.

For bombarding malignant growths X-ray tubes are needed which will stand much higher voltages than those used for X-ray picture taking. Cancers on the surface of the body can be treated with X-rays produced at 100,000 to 200,000 volts, but a malignancy which lies deeper may require rays from tubes which operate on much higher voltages. The principal rays from radium are equivalent to those from an X-ray tube running on only two million volts. Since the immediate plans of the atom-smashers call for tubes which will stand hundreds of millions of volts, medical investigators naturally have a weather-eye cocked to watch their success.

Several large hospitals in the United States now possess X-ray tubes to which a million volts or so can be applied safely. Some of these great tubes are twice the height of a man, and each of them will furnish rays in quantity equivalent to those given out by more than two pounds of radium—$18,000,000 worth. Mere interest payments on the investment in so much radium would come to one hundred dollars for an hour's treatment. Yet the power to operate the most

efficient of these giant X-ray outfits for an hour costs less than thirty cents.

A three-million-volt X-ray tube of the type which has been built for atom-smashing can readily be applied to medical purposes. Since such a tube produces not only more rays but more useful rays than those of any obtainable amount of radium, deeper-lying tumors can be reached with its aid, and treatment times greatly shortened. Such an X-ray outfit costs less than many a sportsman's toy.

"Millions of volts" sounds rather alarming to a patient; but danger from electric shock has been completely eliminated in these giant tubes. All dangerous and scientific-looking gadgets can be kept bottled up in a room into which no one need go while the apparatus is running. The X-rays can be sent through the bottom of the tube into a room below, where the patient reclines comfortably amid attractive surroundings during the short periods required for treatment.

Some doctors believe that high-speed electrons may turn out to be even more useful than X-rays or radium emanations in treating cancer. The faster an electron moves the less does it affect tissue through which it passes, just as a fast bullet breaks a cleaner hole through a pane of glass than does a slow one. High-speed electrons might then be expected to affect less the healthy tissue cells in the first part of their paths, and to do most of their desired destructive work on the diseased cells at the end of their flight, like shells with fuses set to explode in the enemy's trenches. However, much higher voltages than have been available previously will be required to generate electrons with sufficient speed to replace X-rays for cancer treatment. Electron rays from a three-million-volt tube are useful, but ten-million-volt electron rays would

probably be better. The atom-splitting physicists are now able to provide these.

2

RADIUM IS THE BEST-KNOWN RADIOACTIVE ELEMENT, but the radium atom is only one of forty kinds of atoms found in nature which are unstable and which will eventually, at some unpredictable time, explode. When an atom explodes it ejects an electron or an alpha particle (the heart of a helium atom) out of its nucleus at high speed, and also emits some penetrating gamma rays. These rays are identical with X-rays, and are of great value to the physician for destroying malignant cells. As far as he is concerned, a vial of radium is merely a very convenient and portable, but extremely expensive, two-million-volt X-ray outfit.

Before 1896 atoms were supposed to be the ultimate indivisible building stones of matter, and no one dreamed that they could be pulled to pieces, much less that some of them would occasionally blow up of their own accord. In that year the French physicist, Henri Becquerel, was experimenting with the radiant glow that appears on certain minerals when they are struck with light. Because it happened to be foggy in Paris for several days, and no sunlight was available for his experiments, Becquerel left some photographic plates in a drawer with a bit of the mineral, which was presumably not glowing. When he developed the plates he found them fogged. It appeared that illumination with sunlight was not needed in this particular case, and that the mineral had been glowing spontaneously. The glow was ultimately found to result from a combination of two minerals—one which be-

came luminous when struck by rays, and another which was constantly emitting rays of its own accord. These rays, it developed, were produced by the disintegration of certain atoms in the mineral; thus radioactivity was discovered.

As all the world knows, Pierre and Marie Curie later were able to concentrate the substance whose atoms were disintegrating in a portion of the material which Becquerel had been using; and this turned out to be a new element, radium.

Radium has had wide use in the treatment of malignancies, but unfortunately, as a result of the many cures associated with it, the word radium has come to have magical significance, and tonic remedies containing radium have had wide sale as nostrums, some of which are extremely dangerous. The rays from radium are useful, but to use these safely the radium which produces them must be placed where it can be fished out of the body at any time. If radium is eaten, drunk in radioactive water, or breathed into the lungs with air, it tends to be deposited in the bones and begins a slow poisoning process which will be fatal if enough radium is present. Though radium is extremely expensive, ten cents' worth is enough to kill a man if it gets into his bones. Eating five dollars' worth or breathing fifty cents' worth of radium salts will accomplish this. As little as one ten-millionth of an ounce of radium deposited in the bones has been found to cause death within ten years.

Fortunately many of the so-called radioactive waters which are sold as medicine contain a negligible amount of radium and are harmless, though their value may be open to question. However, there are some which do contain radium in relatively large quantities, and these are slow but deadly poison. A few unfortunates who have drunk "radium waters" have found themselves apparently improving in health for a

time, presumably as the result of a stimulating irritation of the blood-cell-producing centers. But shortly thereafter, when enough of the radium has become fixed in the body, a poisoning process of a particularly horrible kind may set in, for the radium atoms lodge in the bones and from this vantage place can bombard the cells of the body to death.

Radium is chemically like the calcium from which bones are made, and the unsuspecting blood stream willingly deposits radium atoms wherever calcium atoms are needed for building purposes. Soon the deception becomes apparent, however, for previously healthy bones, attacked from within, begin to fester and decay. Even after an atom of radium has exploded, the damage it can do is not complete, for it changes into an atom of radon which can again explode, and over and over the same atom, like a six-ball Roman candle, can shoot out its violently destructive rays. It is of no use to wait for all the radium atoms which have been taken into the body to explode, for only half of them will have done so by the end of 1690 years. The only hope is to get some of them out, and this can be done more readily if it be attempted soon after they have been absorbed.

In a number of cases of radium poisoning, it has been found possible literally to rinse some of the dangerous atoms out of the patient's bones. First he is given a medical treatment which causes his bones to lose calcium, and, as the calcium departs, some of the radium is forced out with it, in keeping with its masquerade as calcium. The patient is kept in bed, and before his bones are appreciably softened the treatment is reversed and the body is encouraged to take up fresh clean calcium to rebuild them. When they are again sound the first procedure can be repeated. This rinsing process can be carried out again and again until the patient improves.

The closest co-operation between physician and physicist is necessary for such treatment. The physicist is needed to make delicate measurements with sensitive detectors which tell, at every instant, just how much radium still remains in the various parts of the patient's body, how much is being eliminated through his breath, and how much through his other eliminative processes. Such control of the treatment is made possible only by the sensitive instruments which have recently been developed for research on cosmic rays, on atom-splitting, and on radioactivity. Measurements made with them cause no discomfort to the patient, as their extreme sensitivity makes possible measurements on the radium content of his body by means of a detector placed as much as a yard away.

To achieve such sensitivity all the resources of modern vacuum-tube amplifiers must be invoked, and to them must be added other tricks which have been developed to pick up the tiny burst of energy which is freed when a single atom explodes. A pebble from a slingshot can explode a percussion cap, which in turn can explode enough dynamite to blow up a mountain. Likewise, the energy of the exploding atom can be turned cunningly into channels which will produce an electrical result which is cataclysmic in comparison with the cause which touched it off. So sensitive have these instruments been made that they record a continuous rat-tat-tat when carried above an ordinary sidewalk, in the concrete of which not more than one atom in a thousand billion is radioactive. Small wonder that they will detect the presence of less than one cent's worth of radium in the human body.

While such instruments were developed primarily for studying atomic processes, their medical application is obvious. One can easily imagine the joy of a patient suffering

from incipient radium poisoning when the instruments show that as a result of a course of special treatments he is eliminating radium eight times as fast as previously, and that the amount of radium left in his body is gradually being lowered to a safe level.

[3

THE CREATION OF NEW KINDS OF ATOMS is commonly supposed to have been quite thoroughly completed some years ago, whether in 4004 B.C. or long before pre-Cambrian days. As this is written, however, atoms of varieties never before found are being artificially produced in physical laboratories throughout the world at a rate almost too fast to follow. Youths with cheeks still downy, who but a few years ago were struggling through the bewilderments of the elementary physics textbooks, are discovering new building blocks of the universe. These discoveries are producing profound effects on chemistry and medicine.

The physicist has succeeded in permanently changing one kind of material into another kind—true transmutation of the elements—by bombarding ordinary matter with atomic bullets. But the new atoms which result from a transmutation were, until the advent of the atomic bomb, of little interest except from an academic standpoint. Far more important are the new varieties of temporary atoms which have been found to be produced as an intermediate step. These atoms are mortal, man-made, not in nature's plan.

Such temporary atoms duplicate the atoms of chemistry, but show surprising properties of instability. They may last but an hour, a day, or a month, and are like ghosts allowed to walk the earth but briefly, after which they must depart.

They are much more real than ghosts while they last, however, for no chemist can distinguish them from their normal counterparts. Only deep within their hearts do they differ, and when the hour for their departure strikes, the tiny atomic cataclysm which results can be picked up by sensitive detectors which record the minute explosion as surely as an earthquake recorder will mark the explosion of a ton of dynamite.

Since these tricky atoms are chemically indistinguishable from normal atoms of the same material, they can be used as atomic spies to follow the movements of swarms of normal atoms with which they can be mixed. The airplane machine gunner finds advantage in having every tenth bullet a tracer which leaves a track of smoke behind it and so marks the path of all the bullets; in the same way the chemist and the biologist, to say nothing of workers in other sciences, are finding tracer atoms effective. Mixing undetected with their fellow atoms, these behave normally until the hour of its inevitable explosion arrives for each. Then, like an Oriental spy sworn to self-immolation, each reveals its presence as it is destroyed and so betrays the location of its atomic comrades.

The explosion which marks the demise of such a temporary atom results, in certain cases, in the ejection of an electron traveling as fast as four hundred million miles an hour—fast enough to encircle the earth three times while one snaps a finger. Such an electron is for all practical purposes identical with one produced in a million-volt vacuum tube. Gamma rays, equivalent to the X-rays from a high-voltage tube, are also emitted by the exploding atom. These two sorts of rays we have already seen to be of great medical importance. Now some patients who need treatment with X-rays or electrons

need no longer rest under a gigantic tube, for some ordinary table salt or other suitably chosen harmless material can be exposed for a few minutes to rays from such a tube, can thus be made artificially radioactive, and can then be applied to the proper spot on the patient. Exact dosage is made easy, for only as many radioactive atoms are produced in the salt as are needed, and if the material is left on the patient too long no harm results, most of the atoms having already exploded.

Another feature of the new radioactive atoms which has aroused medical interest is that suggested by the concentration of iodine by the thyroid gland. Some physicians who have worked on the problem believe that when iodine is fed to a patient, practically all of it is concentrated in the thyroid gland within twenty-five minutes. Radioactive iodine atoms can be made by bombarding iodine with protons, the hearts of ordinary hydrogen atoms. If such activated iodine mixed with ordinary iodine is fed to a patient, the physician is able to follow the course of all the iodine atoms through his system by counting the atomic explosions which will be registered on various detectors placed in suitable positions around him.

Now suppose that a patient has a malignant disease of the thyroid gland which needs radioactive treatment. The radio-iodine atoms emit rays which are quite as effective as those of radium, and the bombarding atoms should be carried in the blood directly to the spot where they are needed. Exactly the proper amount of radio-iodine, costing only a few cents to produce in one of the new atom-splitting machines, could then be given to the patient so that when almost every atom has exploded and has done its minute bit of cell blasting, the proper treatment would have been completed. As each radio-iodine atom disintegrates it changes to xenon, an

absolutely inert gas which is harmlessly carried off in the blood stream.

Biologists have always been interested in determining how phosphorus is utilized by various parts of the living body. Chemical methods of attacking this problem have a drawback in that it is necessary to destroy the tissue to analyze its contents, a procedure which may be impossible except in the case of certain parts which the patient can readily spare, such as fingernails or hair. Radio-phosphorus now enables biologists to investigate this problem without destroying tissue. Atoms of radio-phosphorous last two weeks on the average before they blow up. Inconceivably small quantities can be fed to a patient—in a radioactive lemon phosphate! Is phosphorus a brain food? Hold the detecting instrument near the patient's head and count the clicks. Do teeth grow, and do they use phosphorus atoms? Don't bother to pull a tooth, but hold the detector near the teeth and see how many atomic explosions occur.

With electrons and protons, deuterons, and even heavier atomic particles available to be hurled against each of the more than four hundred sub-varieties of atoms which the physicist has found included among the ninety elements of the chemist, dozens of new kinds of useful temporary atoms doubtless remain to be discovered. Already nearly two hundred new varieties of temporary atoms have been produced by physicists in the course of atomic transmutations, and it seems probable that every known element can be produced in one or two temporary radioactive forms. Some have already been created in four or five forms. As higher speeds for atomic bullets are achieved, increasing numbers of new super-chemical reactions should be found.

That one kind of atom can be changed into another by

striking its nucleus with an atomic bullet was discovered in 1918 by Sir Ernest Rutherford. That new atoms so formed are often unstable, and hence radioactive, was first observed in 1933 by Irene and Frederic Curie-Joliot, daughter and son-in-law of the Curies who discovered radium, when they let rays from radium bombard other atoms. This method is still used to some extent, but greater yields of the radioactive atoms can be obtained by using one of the new atom-smashing machines which have been developed to make atomic particles move with high speeds. Two such devices have been particularly successful, one the cyclotron developed by Dr. Ernest O. Lawrence and his collaborators at the University of California, and the other the electrostatic generator which produces high voltages which can be applied to great vacuum tubes, developed by Dr. Robert J. Van de Graaff and his coworkers at the Massachusetts Institute of Technology. Several dozen of each of these devices for producing artificial radioactivity are now in operation or in process of construction in America and Europe.

The electrostatic generator, already mentioned in connection with the transmission of power, uses the static machine principle, modified and dressed up in modern form to produce voltages hundreds of times greater than those produced by ordinary static machines. The forte of the static machine, used so long in doctors' offices to titillate the skin and make patients' hair stand on end, has always been to produce a great deal of voltage without much current, and this is just what is needed to operate giant vacuum tubes.

In the cyclotron, atomic bullets of any one of three or four varieties are swung in circular orbits of constantly increasing diameter, just as David in his encounter with Goliath whirled a stone around his head by means of a leather sling.

A huge magnet is used to keep the particles circling in the proper orbits within an evacuated chamber, and carefully timed electrical impulses keep them swinging around ever faster and faster until they finally emerge at high speeds.

Important new atom-smashing devices which have grown from the cyclotron are the betatron, developed by Professor D. W. Kerst of the University of Illinois, and the synchrotron, to which a number of physicists have contributed and which is still in the process of development. The betatron and synchrotron are especially designed to accelerate electrons to high speeds. With a huge synchro-cyclotron at the University of California, particles have been speeded up to the equivalent of having fallen over a 400,000,000 volt electrical precipice, and have then been found to produce mesons artificially.

The uranium pile, discussed in detail in Chapter XVII, is a powerful source of nuclear rays and of artificially radioactive elements which act as portable sources of useful nuclear radiations. Especially are such piles valuable sources of neutrons, which can be produced in such numbers that with them gold can be transformed into mercury and almost any atom into several others, in quantities which can be weighed, packaged, and sold in commerce.

4

LIGHT, IN ADDITION TO BEING USEFUL FOR SEEING, has its own curative effects. Some physicians consider sunlight the greatest of all healing agencies, but sunlight is not always available. Lamps have now been developed which can be made to radiate not only waves of every one of the visible and in-

visible colors which the sun sends us, but others as well which were never known before. Many of these new light rays are found to have definite germ-killing or curative properties, while others have not yet been tested for possible biological effects.

The spectroscopes and light filters which the physicist has developed to study the structure of matter, and the relationships of matter and energy, have proved very useful in separating light into its component parts for medical use. When a beam of white light produces a curative or stimulating effect, there is always the possibility that only the blue or the red light contained in the white beam was responsible for the effect. When the basic colors have been separated and tried individually, sometimes one color has been found partially to offset effects produced by another—a greater effect being produced by a part of the light than by all of it.

The same long-waved ranginess which enables infra-red rays to penetrate haze for great distances serves the physician well, for it enables these rays to get through layers of skin and fat and thus reveal anomalies of underlying tissues. The sinuses and other body parts, which can often be usefully studied by sending ordinary light through them and looking for shadows, can be penetrated even better with the longer invisible waves. Heating lamps are frequently used to provide infra-red rays which are sent through the skin into the underlying tissue where they soothe cramped muscles and tired nerves. Their application increases the flow of blood, and is said to be beneficial in neuralgic and arthritic conditions.

The effects of light of various colors on mold spores have been strikingly shown by covering a flat plate of glass with gelatin soaked with some jelly-like material which becomes moldy easily. The plate was planted uniformly with the

spores, and was then exposed to the light of the spectrum; long infra-red rays fell on one end of the plate, then came the rainbow array of visible colors, and finally the spectrum of invisible ultra-violet rays falling on the other end. After a short exposure to this complete spectrum, the plate was put in a warm place where any spores which were left alive might multiply and prosper. A few days later the spores were found to have photographed their own death records, for in regions exposed to light of colors which would kill the spores the plate was clear, while in other regions the plate was opaque with mold, the light there having permitted growth, and, with some waves, even stimulated it.

The curative value of sunlight for various serious skin diseases has long been known. Remarkable cures have also been made by focusing on the skin by means of quartz lenses the light from powerful electric lamps. Ultra-violet light kills germs, but in the early experiments the skin was sometimes badly burned while the germs were being killed. Fortunately the rays that did the burning and those that killed the germs were not the same, and it was found possible to filter out the former by sending the light a short distance through water.

When the tiny organisms which produce many diseases are watched under a microscope while they are illuminated with ultra-violet light, they can be seen to curl up and die. Short-wave ultra-violet rays are especially deadly to most germs, and ultra-violet lamps which emit germ-killing invisible rays are being increasingly installed in surgical operating rooms. If a beam of this invisible light be allowed to shine in one end of a solid rod of fused quartz, the light will follow any bends or twists in the rod for many inches, practically without diminution. Such transparent rods are now quite commonly used

to pipe healing and disinfecting radiations into various passages of the body.

Much of the milk that is sold today is "ultra-violet rayed." In large creameries the milk is made to flow from a tank in a thin sheet, and bright batteries of mercury arcs shine germ-killing ultra-violet light all through it. In some large bakeries, loaves of bread and even cakes, of which almost one in seven were formerly lost through spoilage, are now exposed to ultra-violet light from special lamps for a few seconds, with the result that less than one in fifty becomes moldy. The effects of sterilizing meat in this way are also being studied.

Production of vitamin D is closely linked to light, and it is no longer necessary to rely on the ability of the codfish to store in his liver the energy of sunlight which has been gathered up by the salt-water algae on which have fed the small fish which he eats. By exposing specific food materials to light under controlled conditions, the vitamin can be concentrated far more effectively than by any codfish.

The medical use of light has met with such a popular response that many fads have developed, some of which have been carried to an extreme. Indiscriminate exposure of large areas of the body to intense light may do much more harm than good. What is needed is more really scientific study of the effects of light of different colors, both visible and invisible, on human physiology and psychology. For the development of the light-emitting, the light-analyzing, and the light-measuring devices still needed for this purpose, medicine looks to the physicist.

5

THE WHIRLING FORCE which causes a youngster to cling so tightly to the neck of his wooden horse on a merry-go-round, and the ticket-taker of the carrousel to lean inward at such a precarious angle as he makes his rounds, comes effectively to the assistance of medicine in the separation of viruses too delicate to handle otherwise. Mud will settle from murky water merely on standing, but the same mud will take much longer to settle from a viscous substance like honey. Centrifugal forces which pull more strongly than gravity can be used to speed the separation of the mud from the honey merely by whirling the mixture in a circle. If a mixture be whirled two thousand times in a second, a force several hundred thousand times its own weight will gently but compellingly urge each particle toward the outside of its container. Such a pull will quickly separate blood cells from the serum in which they float. A grain of wheat whirled in a tiny circle at so giddy a rate behaves as though it weighed more than fifty pounds.

Small rotating tops have recently been developed which will spin a tiny vial of biological serum at speeds up to a million revolutions a minute. To attain such speeds, friction must be reduced to a minimum, and the top, as it spins, touches nothing solid but is balanced in a whirling jet of air. The limitation which prevents attainment of still higher speeds is the difficulty of getting materials which will stand the great forces involved—the top itself tends to be torn apart by the terrific pull in its own substance. Yet even at the highest practicable speeds, a flashing light has been ar-

ranged to make the whirling tube seem to stand still, and an observer, looking through a microscope, has calmly watched a cell being pulled apart while it whirled under his nose at more than three hundred miles an hour.

Mechanics, as exemplified in the centrifuge, is the oldest branch of physics; but what of electricity, one of the newest? The body probably has more electric currents flowing through it than a telephone switchboard, but most of these currents are weak and difficult to measure, and the body is poorly equipped with electrical terminals. Variations in health and in the tone of various organs are undoubtedly reflected in changes of these currents, but as yet electrical methods of diagnosis have been but slightly developed. How tired a person feels and his general state of health seem to be tied up in some mysterious fashion with differences between the resistance of his body to the passage of an alternating current and to a direct current. Just why this relationship exists, and how it can be used, are as yet not apparent.

In the treatment of disease the position of electricity is more secure. The electric knife has caused great progress in surgery. High-frequency alternating current is sprayed into the tissue from the edge of the knife, and as the tissue is cut the edges of the wound are electrically disinfected and seared, a process which reduces bleeding and promotes healing. In brain operations the radio knife has been found especially useful, for with it electric current can be sent through tumors to shrivel and destroy them, and the dried tissue can be removed through small openings in the skull. In cancer operations this knife may give greater safety, for cancerous cells which might be set free for distribution through the body in the blood stream can be killed by the heat and current, and the ends of the blood vessels which might carry them

off are seared shut. The radio knife is operated by means of alternating current of very high frequency, and is a direct development of the investigations which made radio-telegraphy possible.

Only in recent years have doctors come to realize that a fever may be not the result of an illness but an attempt of the body to cure the illness. Many kinds of germs die at temperatures slightly above normal body temperatures. Doctors have even inoculated patients with malaria germs to produce intermittent fevers—the malaria was less disagreeable and easier to cure than the original disease. When it is found that a vacuum tube can produce just as good a fever as a malaria germ, with no malaria to be cured afterward, there is cause for rejoicing.

The heat generated by high-frequency currents first became noticeable when radio men who were working near high-power oscillating tubes developed temporary fevers. After all, if the insides of vacuum tubes could be heated white hot by such means, why could the insides of a patient not be warmed to a lesser degree?

Listing the contributions of physics to the new medicine could be continued almost indefinitely. Tiny super-candid cameras which, with their own lights attached, can be swallowed by a patient and used to snap a number of views of the inside of his stomach before they are fished up again; electrical speedometers invented specifically to measure cosmic rays but which immediately are found useful to count the rapid heartbeats of a rat; electrical stethoscopes and brain-wave measurers which give such an accurate indication of the state of vitality of a patient deep under the influence of drugs that mental cases hitherto considered incurable can be safely treated—hundreds of such examples can be brought forward

to emphasize the great importance to mankind of close co-operation between the physician and the physicist.

Medicine is growing in effectiveness as it progresses from the status of an art to that of a science. Progress in a science depends to a great degree on the tools which can be forged to aid it in uncovering truth. For many years the principal tools of the physician were his own five senses, but human eyes have bounded vision as human hands have limited strength. With eyes and ears that see and hear where before were only darkness and silence, the modern healer finds in no mere poetic sense that his strength is as the strength of ten. These more-than-human eyes and ears, this beneficent sharpening of the senses, it is the province of physics and the purpose of physicists to continue to supply.

X

GLASS SHARPENS VISION

It adds a precious seeing to the eye.
Love's Labour's Lost

THOUGH glass has now been educated to be one of the most talented substances we know, its most valuable property still remains its transparency to visible light, and its most obvious use is to be looked through. For though the unaided human eye is a very sensitive device, by judiciously supplementing it with a few pieces of glass the penetration of its gaze and its range of vision can be increased several thousandfold; and even the best pair of eyes needs glasses whenever its owner wants to see something very small or very far away. Whether these glasses are to be called spectacles, or telescopes, or microscopes, depends on what is to be seen, but each of these devices is made possible by the fact that glass slows down any beam of light that passes through it.

Light streams across empty space or through the air at a speed of about 186,000 miles a second, but whenever a beam of light enters a slab of glass it is forced to slow its pace to a mere 120,000 miles a second, or even less. Why should this speed limitation make things easier to see? Why should a near-sighted man, to whom everything more than three feet from his head is hopelessly blurred, suddenly be able to distinguish clearly objects a hundred miles away just because he looks through a curved slab of frozen syrup? Why should

putting a piece of glass in the way enable an astronomer to see fifty million stars where before were only five thousand, or a biologist to find wriggling animalcules in what before appeared to be a clear drop of water?

Because light is slowed down in passing through glass, its rays are bent whenever it passes at an angle from air into glass, and again when it re-emerges into the air. Usually the second bending exactly offsets the first, but if the two sides of the glass happen to be set at an angle, as in a prism or lens, the light ray travels off in a new direction. The eye suspects no such deviation from the straight path, and reports unfalteringly to its possessor that any object he may see is in the direction from which light rays from it appear to have come. A magnifying lens is thus a deceitful piece of transparent material whose surfaces have purposefully been curved in such manner that rays of light from distant objects are bent so as to appear to have come from closer and larger objects. So useful is this ability to mislead the eye that the world now uses lenses by the hundreds of millions, and the invention of a new shape of lens can revolutionize a whole industry.

The ability to magnify objects is not the only useful function of a lens, nor indeed its most important function. The eye can utilize only that light which enters its pupil, a hole but a fraction of an inch in diameter; but a lens can be made large and will therefore gather in a great quantity of light, with which it can produce a bright image. A lens is thus a highly qualified light-funnel, able to keep the rays which traverse it from getting mixed. If a lens is of high quality the image it produces will be clear as well as bright, for the picture seen by the eye is formed by piling up a vast number of

tiny light-waves, and the more waves in the pile, the more sharply defined will be the picture.

If an ordinary lens be held in a darkened room and light from a bright distant landscape be sent through it, a tiny image of the landscape can be seen on a piece of white paper held at the proper distance behind the lens. The distance between paper and lens—called the focal distance—depends on how sharply curved are the sides of the lens, and on how markedly the passage of light is slowed by the glass of which it is made. To image objects near at hand the paper must be moved farther from the lens than when distant objects are being imaged. If our eyes, which contain natural lenses, had instead been fitted by nature with lenses of glass, we would indeed need to be a popeyed race, for as we approached a friend to shake hands our eyes would perforce protrude ever further from our heads as we strove to keep him in focus. Fortunately the human eye contains a remarkable lens which is flexible so that its sides can be shaped to sharper or flatter curvature to alter its focal length.

Unfortunately, many of us have eye lenses of faulty shape or adjustment. Surveys have shown that at the age of thirty the vision of more than one-third of all civilized people would be greatly improved by the use of spectacles. At age 41 half the population, at 52 three-quarters, and over sixty almost all people have eyes whose lenses need extra help. Many more people need glasses than wear them, and the gradual breaking down of prejudice against their use, particularly on the part of women, probably accounts for their increase more than does any progressive deterioration in the eyesight of the race.

In cases where there is objection to the wearing of spectacles, lenses of glass or plastic which fit directly over the eye-

ball and are so thin as to be unfelt and unseen can be used. These are even less liable to breakage than ordinary spectacle lenses, since they have the support of the eyeball, but they must be fitted and used very carefully. They cost much more than ordinary spectacles, but are coming into increased favor for athletic and cosmetic purposes. The lenses are kept clean and free from fog by the eyelid, and no disturbing reflections are sent back from their surfaces. They cannot be worn for long periods without discomfort, however.

Important as the contributions of science may have been in sharpening up the vision of many of us who would otherwise have a very hazy view of the world, an even more important use of the lens has been in making realms visible which no human eye, no matter how perfect, could hope to see unaided. Tiny lenses no larger than a pin head, great disks of glass which require special freight cars for their handling—these are the eye-glasses that are opening new worlds to human view.

¶ 2

ONLY A PIECE OF VERY PURE AND UNIFORM GLASS can be used to fashion a lens of high quality. Optical glass must be specially cast so as to be colorless and free from bubbles, streaks, and flaws. A minute quantity of iron or of almost any other metal can ruin an entire batch of such glass. One company made several expensive melts of lens glass which turned out valueless because they all showed the familiar green tint of the cheap glass used for bottles and windowpanes. A disgruntled workman had secretly dropped a small steel ball into each melt. Even the use of steel shovels to handle the sand which is to go into lens glass has been outlawed, for so many

iron atoms were scraped from their surfaces that the resulting glass lost much of its transparency.

After a chunk of clear uniform glass of approximately the proper size for a desired lens has been obtained, its surfaces are ground to the required curvature by rubbing them against curved metal plates sprinkled with wet carborundum powder or some other hard abrasive. No way of molding glass while hot into perfect lenses has yet been discovered, but if ever one is, lenses will become much cheaper. At present the glass surfaces are worn down slowly to the desired shape, and then gradually smoothed with smaller and ever smaller particles of grinding material. The last tiny scratches are worn away with fine particles of powder such as rouge, which, so it happens, in addition to being found useful by ladies to simulate hemoglobin, will give glass a high polish when imbedded in pitch and rubbed against it.

In large optical factories hundreds of lenses are ground and polished at the same time. Several dozen lens blanks may be cemented with pitch to each of a dozen holders, and in a single machine long rows of these holders can be seen rocking back and forth together like dancers swaying to a tune, as the glass whirls under the polishing tools and its surfaces approach perfection of smoothness and curvature.

A lens made from a single piece of glass cannot produce an image of desirable sharpness unless it be used with light of a single color, and in addition is so small that its focal length is much greater than its diameter. The ratio of focal length to lens diameter or aperture is called the aperture ratio, and numbers representing this ratio are usually found marked on the lenses of cameras, written as f/3.5 or f/16 or some such symbol. In the first case the figures indicate that the lens is being used at a diameter which is 1/3.5 of its focal length;

in the second case at 1/16 of its focal length. A diaphragm covering the lens can usually be closed until the aperture is any desired fraction of the focal length. The larger the denominator in the aperture ratio, the more sharply can the lens focus light, usually, but the less light passes through it.

Most commercial lenses have sides curved to fit portions of spheres, because this is the easiest curvature to give to a lens by rubbing it with abrasives. This is usually not the most desirable shape, however, and such lenses have faults called aberrations, which prevent them from producing sharply focused images unless used in a particular way. If a lens brings rays of light together improperly, points which should appear as shiny dots may be pulled out in the image into streaks like the tails of tiny comets, or into other equally undesirable forms. Or straight lines in the object may appear curved in the image, this effect giving rise to distorted pictures if the lens is used in a camera. Or the lens may form an image which would be sharp everywhere only if photographed on the surface of a sphere, so that a photograph album would of necessity look like a pile of trimmed derby hats. However, by putting together a number of individual lenses of different shapes and sizes, each a piece of a different variety of glass so curved that it will offset the limitations of the other pieces while providing some good qualities of its own, physicists have developed hundreds of varieties of multiple lenses, each of which will produce sharp images if used in a particular way.

Lenses which contain many pieces of glass are wasteful of light, for at each surface some light is lost from the beam by reflection, and this may be scattered or reflected to parts of the image which should be dark, thus giving less brilliant pictures if used in a camera. Far better than using many

pieces of glass, when possible, is the use of new kinds of glass which give the desired result with fewer component lenses. As more varieties of glass become available to the lens designer, he finds ever simpler the invention of lenses of high quality for new uses.

In the early days of glass-making, when the art was ruled chiefly by cookbook methods, England was the center of glass manufacture. During the middle of the last century, however, German manufacturers called on science to help them, and soon took the lead. The physicist Ernst Abbe showed, by theoretical calculations, that the microscope could not possibly be made to give sharper or larger images if lenses must be made from the few optical glasses then available. He suggested that chemists be set to investigating the effect on its optical properties of adding other chemicals to glass; perhaps a few borax or lead atoms, while not coloring the glass, would have beneficial effect on the amount by which it slowed the passage of light. So was laid the groundwork of the great Jena optical glass industry, which for years was pre-eminent in the world and only in the 1930's began to be rivaled by similar American developments. Rule-of-thumb and secret cookbook recipes have had little chance of survival when placed in competition with scientific investigation.

The science of lens design is still in its infancy, and great opportunities still are to be found in this field. When a new type of lens is needed the paths through it which will be taken by the rays of light must be laboriously computed—a job which could be done much better by a machine, if someone could design the machine. Another machine badly needed is one which would turn out in quantity lenses having non-spherical surfaces.

An important recent development is the production of thin transparent films on glass which reduce the reflection of light, which is what ordinarily makes a clean glass surface visible. So-called invisible glass is produced by condensing on to the glass surface in vacuum a very thin layer of a suitable chemical salt, which "eases" the light wave into the glass surface so that less of it is reflected. This is of great importance in lenses which contain many components, and are likely to produce objectionable "flares" by reflecting light into parts of a scene where it does not belong.

3

THE TELESCOPE OF THE ASTRONOMER, being designed primarily to gather light from stars and planets a great distance away, consists usually of a large lens whose function is to collect as much light as is needed to produce an image which is bright and sharp, and a set of smaller lenses with which this image can be magnified. The bigger the first lens the better the telescope, provided the shape of the lens be held within a millionth of an inch of the proper curvature to guide the light rays properly into the image. Strangely enough, the bigger a telescope the smaller a star appears in it. This is because most stars are so far away that they would appear as mere points of light in a perfect telescope, and the larger the lens the more neatly can the light waves be piled together to form this tiny point of light.

One of the largest lenses yet made is about 40 inches in diameter. With this lens, which is in a telescope at the Yerkes Observatory in Wisconsin, the moon when 200,000 miles away can be brought to within a hundred miles for seeing purposes. Many telescopes exist which are more powerful and hence

can bring the moon even closer, but these use mirrors instead of lenses to gather the light waves and guide the rays.

Clear glass, free from internal streaks and strains, is very difficult to produce in pieces as large as four feet across. Therefore the size of telescope lenses is severely limited, especially since two large pieces of different kinds of glass must be used for each telescope, two lenses being placed together so that one improves the image formed by the other. Since each lens must be ground and polished separately, four glass surfaces must be shaped, each to within a millionth of an inch.

Far simpler than to attempt construction of such large lenses is the use of a concave mirror to gather the light, for with this the rays can be thrown into an image merely by reflecting them in the proper directions, and no clear, transparent material is necessary. Glass still remains the most useful substance, but its purpose now is merely to furnish a hard inflexible support for the thin metallic coating which forms the mirror itself. Glass is used for telescope mirrors because it is hard and brittle and can be given a high polish after it is ground to the proper curvature, and because it expands less when heated than do metals or other materials.

Greater and greater have become the diameters of the large telescope mirrors, through 40 inches, 60, then the great achievement of the 100-inch Mt. Wilson telescope, and more recently the gigantic 200-inch mirror ordered by the Rockefeller Foundation and the California Institute of Technology for erection in Southern California. This great mirror gives mankind a 17-foot monocle with which to scan the depths of space. With it the light of a candle 40,000 miles away should be clearly visible—how far a little candle throws its beams depends on how you look at it!

The peak of achievement in glass manufacture which made this telescope possible came in 1934, when as a result of careful planning the Corning Glass Works successfully cast a disk of glass more than two feet thick and seventeen feet in diameter. If the disk had been cast solid it would have weighed more than forty tons, but by designing a ribbed structure with a smooth upper surface, the weight was reduced to twenty tons and a thinner construction could be used. As it was, the disk was so large that it had to be sent across the continent by an indirect route to avoid tunnels and low-hanging bridges. It was stood up on edge in a special railway car, with only three inches to spare between its lower edge and the railroad ties beneath.

The same qualities in a special glass which made glass frying pans possible made this giant mirror practicable. Astronomers knew that if so large a mirror was to be usable it must be constructed of some flinty substance which would hold its shape to closer than a millionth of an inch under the temperature changes to which it would be subject. They knew that fused quartz would be ideal, but it had been tried and found too expensive for use in a big telescope. The glass manufacturers must try to work out a formula for a new glass which, if not quite so good as quartz for the purpose, would at least be good enough. They set to work, and before very long succeeded in developing a kind of super-Pyrex glass which when heated expanded even less than the old variety. This glass was used for the casting of the giant mirror.

That the same material which is best for looking a trillion miles into space happens also to be best for frying a chop is not merely a coincidence. Neither the telescope mirror nor the frying pan need be transparent, but they must share a disinclination to change size and shape suddenly when heated

or cooled, the first because it would warp, the second because it would shatter. The astronomers got their mirror when the cooks got their frying pans.

It seems inevitable that once the 200-inch telescope has been in use for a few years astronomers will be wanting one still larger, but to increase the sizes of telescopes further will not be immediately practicable, for air waves in the atmosphere above the mirror cause the star images to dance about so that magnification of more than 2000 diameters is useless.

While it will probably never be possible to keep the stars from dancing as the atmosphere boils and shimmers, it may be possible to make them stand still long enough to have their pictures taken by making the telescope camera automatically jump around to follow the jumping of the star images. It has been suggested that a photo-electric cell could be used to anchor the camera to the light of some particularly bright star. Whenever the star image jumps slightly to one side the photo-cell will decide which way the photographic plate should be moved to keep up with it, as well as how far and how fast. All these things must be done within hundredths of a second, and the problem will be a difficult one to solve technically, but should be not at all impossible to men of imagination and resourcefulness.

4

THE TELESCOPE GIVES US A GREAT EYE for the distant, and the camera gives us an eye that remembers. Physics has given us a third eye, the microscope, for peering into the world of things minute. In 1870 there were only fifty microscopes in this country; by 1948 there were more than fifty thousand.

Better glass, cleverly formed into scientifically shaped pellets, helped make this growth in use possible.

The real purpose of a microscope is to make us successfully short-sighted. To see tiny and yet tinier objects, we need lenses not larger, but more sharply curved so that they can be placed ever closer to the object under observation. Ultimately we reach a point where the lens is so small that greater magnification does no further good. The difficulty now lies in the light waves themselves, for too few of them are received into the lens to produce a sharp image. Enlargement by four thousand diameters is as much as is practicable with visible light, for greater magnification gives merely a larger blurred image, with the blurring magnified quite as much as the image. All science from medicine to metallurgy would be benefited greatly by new microscopes which would give clear enlargements of more than four thousand diameters; ten thousand diameters would be very desirable, or, while we are wishing, scientists may as well ask for a hundred thousand.

Provision of such microscopes, if we are ever to get them, must lie with fundamental physics, for the difficulty is not with the present-day instruments so much as with light waves themselves. A wave of yellow light, though only one fifty-thousandth of an inch long, is yet too coarse to reveal much about a particle of matter smaller than itself, just as the daintiest finger is far too coarse to be used in lieu of a needle for playing a phonograph record. To feel the shape of an object satisfactorily with our eyes through the medium of light waves, these waves must be comparable in size with, or smaller than, the detail which is to be seen with their aid.

A partial remedy is to sharpen up the seeing by using shorter light waves. These waves lie in the invisible ultra-

violet region of the spectrum, to which ordinary glass is not transparent. So the call goes to the glass manufacturer to develop a glass which will be transparent to shorter waves. More mixing, melting, and testing go on, and a few months or years later the scientists emerge from their laboratory with a new glass which will transmit ultra-violet light. From this material new lenses can be constructed for microscopes of new form, and by such means the limiting magnification has already been almost doubled, and enlargements of eight thousand times are made entirely practicable.

To make still greater magnification valuable by using even shorter waves, the microscope must be placed in a vacuum or in a container of hydrogen or helium, for air is opaque as the blackest ink to those ultra-violet rays which are less than about a hundred-thousandth of an inch in length. Nor can ordinary photographic plates be used to record the invisible images produced by such a microscope, for they are insensitive to these very short waves. Fortunately special plates which will serve have already been developed by spectroscopists.

A new type of microscope has recently been developed by Edwin H. Land, whom we shall meet later as the discoverer of Polaroid. Land makes use of photography to take pictures with an ultra-violet microscope in three colors, which are then combined to make a color photograph. The colors are not actually those of the material being photographed, but rather are analogous to those they would have if our eyes could see ultra-violet light. In this way a wholly new type of observation is made available, which is especially valuable to the biologist. Often the abnormal tissues in which he is interested show variations from healthy tissue only in terms of the ultra-violet colors which the new microscope transforms into visible colors.

Other possibilities are opened if other kinds of waves than light are used for making observations. X-rays are sufficiently short to reveal the structures of the very atoms themselves, but they do this indirectly and show little about such relatively large creatures as bacteria and microbes. Electron waves can be used to produce greatly magnified images, and by using these in combination with light waves, images magnified thirty or forty thousandfold have been produced. Perhaps the biologist of the future will be feeding osmium or barium meals to his paramecia so that the internal arrangements of unicellular organisms can be made evident by dancing electron waves.

Each increase in available magnification means much, and already a photograph of a clump of matter less than a dozen atoms across has become possible. The biologist realizes that the ultimate living creature must be cornered somewhere. It cannot be smaller than a fairly complex molecule, which must in turn be made up of a number of atoms whose diameters we know.

¶ 5

WHEN A LENS DESIGNER traces the path of a beam of light through a lens, it matters little whether he considers the beam to consist of a train of waves or a stream of photons. But there are certain phenomena which, while not contradicting the idea of photons, absolutely require the conception of waves traveling through space for their understanding. Such phenomena are those involving polarized light.

A beam of light emitted horizontally from a candle flame contains electro-magnetic waves which can be thought of as vibrating up and down, from left to right, and in every conceivable direction at right angles to the direction in which the beam is traveling. Such light is said to be unpolarized; but if

it be sent through a piece of transparent tourmaline crystal only part of the light will emerge, and this light is said to be polarized, for all its waves will be found to be vibrating in one plane. This can be demonstrated by sending the beam which has emerged from the crystal through a similar crystal. Only if the second crystal be turned so as to have a definite orientation relative to the first will much of the light pass through; if either crystal be rotated relative to the other the amount of light passing through will be decreased or increased, and when either is turned at right angles to the position of maximum transparency no light will pass. The polarization of the light is caused by rows of atoms in the first crystal suppressing all waves except those which vibrate in a preferred direction; and how much of the light can get through the second crystal depends on how well the rows of atoms in the two crystals are lined up. Thus inventors are provided with a means of changing a pair of crystals from clear to opaque merely by rotating one of them.

Polarized light has been a useful research tool for more than a century, but only recently has it found widespread application in industry. Strains in glass can be made clearly visible by sending polarized light through the glass. When a piece of glass is viewed in the strain-revealing apparatus, beautiful colored bands appear in it, green and pink and blue and dozens of other hues. These colored bands shift to one side wherever the glass is compressed, and to the other side wherever it is expanded. By measuring the shift of the bands the exact number of pounds tension or compression in any part of the glass can be determined. Touch the side of a piece of glass with a hot iron while it is being viewed in such a strain-analyzer, and the expansion of the glass around the warmed spot can be seen clearly as the colored bands twist and writhe.

Since the breaking strength of any kind of glass can be accurately measured, the shift of the bands tells at once how dangerously close the glass is to being shattered by internal strains.

Cellulosic materials also produce colored bands when strained and viewed in polarized light. From such materials engineers can fashion celluloid models of axles or bridges or dirigible balloon frames, and by means of polarized light observe where the greatest strains are concentrated. Then they can devise improved models which distribute these strains more evenly, thus reducing possibility of failure under crucial conditions. Some models can actually be operated with polarized light passing through them, and the surgings of the forces in them can be watched and photographed. Typical strain bands are shown in the accompanying photographs, which, while less imposing than they would be in natural color, are revealing nevertheless.

Light and sugar may not appear to have much in common, yet samples of every shipment of sugar that has passed through at least one Customs House have been tested for purity and concentration with polarized light. When sugar is dissolved in water the transparent syrup thus formed will progressively rotate the direction of vibration of any polarized light waves sent through it, and the more concentrated the syrup the greater is this rotation. The amount of rotation can thus be used to measure the concentration and constitution of the sugar. Some varieties of sugar give the light beam a right-handed twist, while others twist it oppositely; strangely enough, though two samples of sugar may differ in this one respect only, certain bacteria can be found which will eat only the right-twisting sugar, and others only the left-twisting.

Dextrose is a common sugar which gets its name because it twists light in the right-handed direction.

Perhaps the most striking effects which polarized light makes possible are those involving color. Mica, cellophane, and many other transparent substances separate light which is sent through them into two beams which are polarized at right angles to each other. When a sheet of such material is placed between two polarizing crystals and white light is sent through them, colors of great purity may be produced by the suppression of certain waves in the white light. Which particular hue will be seen in a given spot depends on the thickness of the material through which the light is made to pass, and on how the polarizing crystals are turned relative to one another. By rotating one or both crystals a beautiful pink can be changed to a deep azure, brilliant greens to vivid magentas, and dozens of varying hues made visible which resemble the iridescent colors of a butterfly's wing rather than the pigments of a painter's palette. Colored pictures in pure light can be produced by sculpturing the desired subject in partial relief on transparent cellulose nitrate or acetate, illuminating with polarized light, and viewing or projecting the light through a polarizing crystal.

The chief drawback to such experiments in the past has been that even small tourmaline crystals are expensive, and tourmaline is not particularly good for producing polarized light because it weakens and discolors the light which goes through it. A better method of polarizing a beam of light was devised by the physicist William Nicol in 1828. He cut crystals of clear calcite at an oblique angle and cemented them together in such a way that the undesired portion of a beam of light was shot off to one side and absorbed in black paint, while the remaining light passed through, polarized and un-

diminished. Until recently Nicol prisms have been the most satisfactory available means of obtaining polarized light, but they are heavy, fragile, and very expensive except in sizes under an inch in diameter, and are impossible to obtain in sizes as large as are needed. It has long been recognized that if some simpler method of polarizing light than by shining it through lumps of crystal were available, use of polarized light would grow by leaps and bounds, and many pressing industrial problems could be solved. Such a method has now been perfected in the development of materials which can be produced in large sheets, and which polarize all light passing through them. The story of the development of these materials is an interesting example of how barriers set by nature can be cleverly sidestepped, with results of great advantage to science and industry.

6

In 1930 a timid Harvard sophomore named Edwin H. Land discussed, before a group of physics students and teachers, the possibility of producing a polarizing material in sheets. He had an idea as to how the problem might be solved, and had succeeded in partially solving it, but was taking college training in physics so that he might determine how best to solve it completely. His idea was to polarize light, not with a single large crystal, but with myriads of tiny crystals piled side by side in sheets of transparent cellulosic material, with all their atoms oriented similarly so that they would all affect light in the same way.

Today the material on which Land was working has been improved to the point where it can be manufactured commercially in large sheets, which are produced in vast quantities

under the trade name "Polaroid." What a wonder-working "celluloid" this is, with its light-polarizing properties! Look at a light through two superposed sheets, and by turning one sheet the light can be made to change in intensity from maximum brightness to complete darkness.

As long ago as 1852 Dr. William B. Herapath had found that small crystals of sulphate of iodo-quinine would polarize light like tourmaline crystals, but would even more strongly absorb half of an ordinary beam of light and transmit the remainder as polarized light. Herapath saw that this property should be valuable, but was successful in making only small crystals. Since his day large crystals have been grown successfully, but now Land's method, and one or two others, have turned out to make them unnecessary, for thin polarizing screens are more convenient and effective.

Land's problem was to imbed millions of tiny polarizing crystals in cellulose acetate in such a way that their rows of atoms were all lined up so as to affect the light uniformly. Fortunately the crystals are shaped like long thin needles, and he could be sure that the atoms would be correctly aligned if the needles were all laid parallel. After trying various electrical and mechanical methods of turning the crystals all in the same direction, Land finally hit on a scheme whereby this could be carried out automatically in a machine, much as needles can be swung into line by throwing them on a piece of rubber and stretching it. Enough crystals are piled together in a viscous cellulose acetate matrix to ensure that no light can pass through without traversing a number of crystals; when the matrix hardens the resulting sheet is found to polarize light almost completely.

The crystals used in the polarizing screens are so tiny that each is thinner than the light waves are long, and more than 50,000 crystals would have to be piled together to give a

thickness of one inch. A polarizing sheet can, in fact, be magnified 1100 times without making individual crystals visible or showing unevenness in its polarizing properties.

At present the principal use of polarizing screens is to eliminate glare, and this they accomplish excellently. The glossy paper of a book, the pavement of a concrete road in the hot sunshine, the top of a varnished desk or table, all act to some degree as mirrors, and light which is reflected from their surfaces produces glare. Light which is scattered irregularly from uneven surfaces is to a considerable degree unpolarized, even though it may have been polarized before reflection. Light, regularly reflected, as from a mirror, is strongly polarized by the mere act of being reflected, however. Just as a loose group of sticks oriented in all directions, if thrown against a smooth floor, will bounce with most of the sticks turned parallel to the floor, so a beam of light bounces with most of its waves turned to vibrate parallel to the mirror. A polarizing screen, with its power to stop or transmit polarized light, can be turned so that it will cut off most of the regularly reflected light, which causes glare, but will affect only slightly the scattered diffuse light which is needed for vision.

Desk lamps are now being made which are covered with polarizing screens, so oriented that only light waves are passed which are vibrating in such a direction that they will not bounce well from table tops; and glare is greatly reduced by the use of such lamps. In up-to-date museums paintings are illuminated with polarized light to reduce glare from their varnished surfaces. When this glare is removed the effect is so marked that it must be seen to be appreciated.

Sun-glasses can be fitted with double disks of polarizing material, with the inner disk arranged to be rotated. Twisting this inner disk will change from maximum brightness to almost total darkness the amount of light which gets through

the two screens. If the wearer tires of gazing on the hot sands of the beach and wishes to converse with a friend, he need only rotate the rims of his glasses until increased transparency makes recognition comfortable.

A hoped-for application of sheet polarizing material has been to eliminate headlight glare from automobile driving, but special problems of heating and of light efficiency have interfered. If all auto headlamps were covered with polarizing screens, and a small polarizing disk were affixed to the windshield in front of each driver at night, direct light from an approaching headlight could be almost eliminated, while light scattered from the side of the road, needed for seeing, would be reduced much less in intensity. To compensate for this loss in brightness, automobile headlamps must be stepped up in power, however, for even with perfect polarizing screens, much of the light emitted is thrown away in the act of polarization; and then, after scattering from the roadside, much is again thrown away in observing. Headlights about three times as bright as those used at present would be required, and the needed power for operating headlight lamps would put a severe strain on the electrical system of any car. This, together with the fact that the screens absorb half the light in the very act of polarizing it, and hence would become very hot, has thus far prevented this desirable application.

Light is already one of the most powerful tools available to the scientist for investigating nature, yet many further uses of light await discovery. Vision is that one of the human senses which gives greatest penetration into the outer vastnesses of space and into the inner world of things minute. Scientists must learn still better how to bend, polarize, reflect, and otherwise coddle light rays into position, that they may be made even more revealing.

XI

EYES FOR THE MEMORY

Oh call back yesterday, bid time return.
King Richard II

IN the Middle Ages there lived an imaginative inventor who, leaning over a quiet pool on a clear summer day, saw himself and the surrounding landscape mirrored in the water. "Ah," thought he, "if I could only freeze this water solid, and thus by some magic hold this tranquil scene permanently recorded within it! Then later, in busier hours, I might gaze into its frozen depths and recapture more vividly in memory the serenity of this peaceful day."

Freezing the glimpse of a moment in water will not, alas, make it permanent, but now we take for granted that a much less cumbersome process will do so; we load a camera with film, point it at the desired scene, and trip a lever. So familiar is this procedure that we are likely to forget that it governs an extremely complex train of events which is successful only because it is held under rigid scientific control. Using a brush of light rays even more tenuous than the "comet's hair" of Kipling's poem, the camera lens paints its picture by informing each of a myriad of tiny crystals of silver salt in the film whether it is to deposit or to withhold the infinitesimal store of silver it contains.

At least forty billion photographic exposures are made each year, yet photography is only now emerging from the status

of a cookbook art and becoming a science. In fact, only recently have scientists discovered even approximately what occurs in a photographic film when it is exposed to light.

There are three principal fields of photography, which differ greatly in their needs and methods. The amateur photographer is usually interested in preserving glimpses of the past by means of photographic prints on white paper which he mounts in albums. To meet this demand, acres per day of the whitest paper obtainable are being coated with sensitive photographic emulsion and spread in half-mile lengths to dry in dark, dust-free, air-conditioned tunnels.

Commercial photography concerns itself chiefly with the wide dissemination of the images of real or imaginary events of the present, and photographs made for this purpose are usually transferred to printing blocks by the half-tone or some other process, so that a hundred or a million copies can be printed on paper with ink, to illustrate books and magazines and fill the growing needs of advertising.

The youngest and most robustious commercial field of photography is motion picture entertainment, primarily concerned with recording events which do not happen at all. So that many persons can observe these events simultaneously, the pictures are copied photographically on transparent film for projection on screens in greatly enlarged form. More than a hundred million persons attend the "movies" each week, and to fill their demands for entertainment hundreds of feature pictures must be in constant production. Since a motion picture requires about a mile and a half of film, and from 100 to 500 copies of each picture are distributed, each uses an average of 500 miles of coated cellulose nitrate. In some motion picture plants a million feet of film is processed during every normal working day.

Quite as important as these three great flourishing fields of photography is scientific photography; scientists have eagerly made use of this eye which does not merely remember, but can endlessly multiply its own records, and with which the passage of time can be slowed down or speeded up. The physician and the biologist rely less and less on visual observation, and use cameras increasingly with their microscopes, their X-ray machines, and their spectroscopes. By expanding the scale of time with the low-speed motion picture camera they can watch the growth and division of cells in the body, observe bacteria and similar tiny organisms rounding out their rapid lives, and thus make observations of a sort which give an insight into living matter impossible to obtain by any other means. Furthermore, the camera can see with light to which the human eye is insensitive, and many happenings otherwise invisible are caught by the ever-watchful lens. The hand is not quicker than the eye of the camera, for this can now catch and record events occurring in as little as a millionth of a second; and "quicker than a wink" means little in scientific photography when five hundred separate photographs can easily be made in less time than a human eye can be closed and opened once.

By fitting his giant telescope with a camera the astronomer can locate countless celestial objects which are invisible to the human eye, for the photographic plate is unhurried and can gather faint light for hours on end. By using the camera to speed up time, he can watch giant storms whirling across the face of the sun, raining down torrents of lead and iron and copper vapors from metallic clouds in solar hurricanes.

In engineering, as in science, photography is found very useful. How many a tired surveyor, his wading boots cast aside, has pored gratefully over maps made by assembling

photographs taken from the warm cabin of an airplane! How much easier it is to lay a ruler between two mountain peaks on such a photograph, than to drag a heavy chain through the forests and across the swamps which may actually separate them!

The scientific and technical applications of photography, like its artistic applications, are indeed endless. Where no human eye can hope to go—into the depths of the ocean far below the plumbings of any bathysphere, down the gullet of a living patient, carried up into the super-stratosphere by giant bubbles of gas-filled cellophane or rubber, or in swishing rockets—there the camera can go, recording what it sees for men later to read.

2

WHAT A DIFFERENCE IN SPEED there is between the photography of a few decades ago and that of today! Then, a person sitting for his portrait, after having had his face dusted with flour to brighten it up a bit, was forced to hold one position for twenty minutes with his eyes closed. Now, a modern "candid camera" can catch the image of a swooping airplane in a thousandth of a second. Modern cameras are so much faster partly because they have lenses which gather in more light, but even more because modern photographic films are several thousand times more sensitive than old-fashioned plates. A picture which can now be snapped in one-fiftieth of a second would have required an exposure of ten minutes in 1860, while in 1820 it could not have been taken in less than a day, using identical cameras in all three cases.

The young lady who pastes a leaf on one bare shoulder and finds its form outlined in tan after a week at the beach is

making use of an elementary type of photography. If she could sit still for days in a dark tent, with a lens mounted in the wall throwing a bright image of the beach on a patch of her skin, she might thus produce a real photograph, for light from bright spots in the landscape would darken her skin wherever it struck. This darkening is caused by a photochemical or light-induced reaction, in which a dark pigment called melanin is produced by the action of the light. Hundreds of such photochemical reactions are known, in which light darkens (or in some cases whitens) a pigment to a degree which depends on the brightness of the light. Any such reaction can be used for photography, but films utilizing most of them would be so insensitive as to be useful only for making blue-prints or for similar purposes where plenty of illumination is available.

Just a century ago, after more than twenty years of experimenting, Nicéphore Niepce and Louis J. M. Daguerre discovered one of the processes which made modern photography possible, while at about the same time Fox Talbot discovered another. These discoveries involved methods of chemically amplifying a photographic image, and did for photography what the vacuum-tube amplifier did for the radio, telephone, and phonograph. No longer was each feeble ray of light required to do all the work of painting its portion of the image by producing a dark deposit of silver where it struck the plate. Now the light need merely sketch out the desired image; then this "latent image" could later be turned into a real image by chemical "development." In this process chemical forces are used to perform the actual work of pulling and hauling electrons about and depositing silver atoms, which is necessary to produce a black and white image.

Chemical amplification can be readily illustrated. Suppose

that a lazy farmer has a field to plow. Since this farmer prefers shooting to plowing, he decides that he will sit in a chair and with his rifle shoot the field full of holes until its soil is sufficiently plowed up. This slow process is analogous to exposing an old-fashioned photographic plate of the type used before 1839 to the rain of photons in a beam of light. But now let the farmer become scientific; let him bury small vials of nitroglycerin at three-foot intervals all over his unplowed field, and then sit in his chair and start shooting. If we suppose him to be a better marksman than farmer, each bullet will set off a small explosion which will loosen the soil in an area a thousand times greater than that plowed by the unaided bullet, and the surface of the field will be pulverized in short order. The farmer has used a process of chemical amplification; his bullets controlled the plowing of the field, but the nitroglycerin furnished the energy which did most of the work. The analogy between plowing a field and exposing a photographic film would be better if the farmer could first shoot up his field, and then, by covering it with a sprinkling of nitroglycerin, produce an explosion wherever a bullet had struck! Both examples illustrate chemical amplification, however.

A modern photographic film consists of a strip of cellulose nitrate or acetate on which is coated a dried emulsion of silver salts in gelatin. This emulsion forms a horny layer containing myriads of tiny crystals, several billion in each square inch of film. These crystalline grains range in size from a few giants, which may be one-fifth as long as a piece of tissue paper is thick, down to others too tiny to see with the most powerful microscope.

In a darkened room the effect of light and development on these transparent grains can be watched through a micro-

scope. Here and there tiny black specks can be seen appearing in the grains, and as development proceeds these grow larger and thicker. Each minute crystal in which a black speck appears ultimately changes completely into an opaque lump of silver, looking under the microscope like a miniature piece of coal. Silver, when spread in a smooth layer, is bright and shiny, but in a fine powder it is very black indeed. When seen under high magnification a photographic print appears like a vast snow-covered field on which designs have been marked with flattened piles of coal.

The early developing processes did not give the entire story of increased sensitivity, however, for the sensitivity of a modern film depends markedly on how it is produced and on the kind of gelatin that is used in its preparation. Much more carefully prepared than the gelatin used for desserts, that used for coating films is of a special kind made from pieces of calfskin too small to be useful in the leather industry. For a long time the difference between gelatin which would confer marked sensitivity on an emulsion and that which would not remained obscure, but careful investigation traced the source of the "good" gelatin to calves whose mothers had grazed in fields where mustard grew. "If cows did not like mustard there would be no motion picture industry," says Dr. C. E. K. Mees, director of the research laboratories of the Eastman Kodak Company. "Gelatin from rabbits is no good for photography, because rabbits don't eat mustard!"

Now, however, science (in the persons of Dr. S. E. Sheppard and his colleagues on the staff of the Eastman laboratories) has solved the problem of producing faster emulsions, for these chemists have succeeded in dissolving from sensitive gelatin a material which makes even rabbit gelatin sensitive, and have also learned how this sensitizing material can

be produced artificially. It is a derivative of mustard oil, and apparently the sulphur atoms which it contains are necessary to furnish a focal point for the beginning of development. Only a drop of this magic distillate is needed to increase a hundred-fold the sensitivity of a whole ton of emulsion—enough to coat acres of film.

Only recently has a clear idea been attained regarding what occurs when light strikes a photographic film and the film is developed. The role of the mustard oil, and in fact the entire photographic process, has finally been explained with the aid of the quantum theory of modern physics. In the original process of photography, each photon of light which struck a photographic plate could set free but one atom of black silver from the molecule of transparent silver salt in which it was imprisoned. In the modern process a few thousand photons, striking a crystal of the salt, affect it so that when placed in the developer every silver atom in it is set free, and the entire grain is changed from white to black by this freeing of billions of atoms.

The larger the grains of silver salt in an emulsion, the more sensitive will it be, but if the grains are too large they may become visible when the picture is enlarged. Different manufacturers have evolved different ways of increasing film sensitivity without increasing grain size, most of which involve heating and chemical treatment of the emulsion. As the physics and chemistry of the photographic process become better understood, secrets of "cookery" are becoming less and less important.

3

THE TINY VEST-POCKET CAMERAS OF TODAY, which weigh only a few ounces yet can take several dozen pictures on one loading, are far different from those of the period before 1880, when any photographer who wished to carry his camera with him had to transport an outfit weighing more than sixty pounds. And as cameras became lighter they became better and cheaper; in 1915 the cost of an average camera was $35, but by 1935 one could purchase a camera for $15 which could respond to dimmer light in shorter time.

From the standpoint of simplicity the world's first camera was better than the most recent, for no lens at all was used, no focusing was needed. Light was allowed to enter a dark box through a tiny pinhole instead of through a lens, and a sharp image could be obtained on a film placed anywhere behind the pinhole—the farther back, the larger the picture. Very little light comes in through such a pinhole, however, and to keep exposure times from being endless a lens is used to bring in more. Unfortunately, the larger the lens the more does it differentiate in focus between close objects and those far away. To take large pictures, lenses must be made as large as convenient, to collect as much light as possible; but they are provided with iris diaphragms which can be "stopped down" to make the lens opening smaller when greater "depth of focus" is desired.

A small lens of short focus has an important advantage over a large lens in that, besides being cheaper, it requires less adjustment of focus. The large lens must be moved farther from the film if objects closer than thirty feet are to be focused

sharply, but to a very small lens the outside world is relatively farther away, and since every object more than three feet away appears to be a great distance off, it images all with uniform sharpness. A camera provided with a lens of less than half an inch focal length need never be focused after the first time, so its lens can be permanently adjusted at the factory. Small motion picture cameras have lenses of fixed focus, thus giving the operator one less adjustment to remember.

A small lens can be made as fast-working as a large lens if its aperture ratio is the same, but the pictures it produces will be correspondingly smaller. However, a small negative can be enlarged to give a positive of the desired size, and modern cameras are usually arranged to take much smaller pictures than those of the past, the only limit being the size of the grains in the emulsion, which must be small enough so that they will not be visible in the enlargement. As research shows how to make sensitive emulsions with still smaller grain size, more pictures will be obtainable on a given area of film, cameras will become still smaller and lighter, and cheaper lenses of smaller diameter and focal length will serve.

The candid camera owes much of its popularity to its ability to take a large number of pictures on a film only an inch wide and three or four feet long. Future cameras may show this trend accentuated; they may be built to contain several tiny rolls of film, any one of which can be selected at will, so that color film, extra-rapid film, or film for use by artificial illumination can be interchanged like the colored leads in some modern pencils. If the graininess of the emulsions can be made still finer without loss of sensitivity, a strip of film half an inch wide and a foot long may be used for a hundred or more snapshots.

Not the least problem of taking photographs is to keep

from under- or over-exposing the picture. Though our eyes report only a small difference in light intensity between a sunny day outdoors and an artificially lighted room, more than 1000 times as much light may be available in the first case as in the second. The brightest highlights in any scene which is to be photographed are seldom more than fifty times as bright as the deepest shadows. Modern film is prepared to darken in proportion to the intensity of light falling on it over a range of about 1000 to 1, though this range varies with the brand of emulsion. Thus considerable latitude is left the photographer in deciding how much exposure to give in order to avoid making shadows too dark or highlights too light.

Three adjustments are available to control the amount of light striking the film from any scene. These are the speed of the emulsion, the time of exposure, and the lens aperture. Film speeds vary over a range of 10,000 to 1, though the films ordinarily sold to amateur photographers vary in speed over a range of only about 10 to 1. The time of exposure can be adjusted, with a good camera, to any value between 1/1000 of a second and as long as the camera and object being photographed can be kept at rest. A lens whose iris diaphragm is set at f/1.9 gathers about 1200 times as much light as one set at f/64. These three methods together make available a range of about ten trillion to one in the amount of light striking the film. Yet photographers have little difficulty in adjusting exposures properly.

A little bit of practice makes one surprisingly good at judging light intensities, but the surest way of getting correct exposures is to use an exposure meter, a photo-electric cell calibrated to measure the light available in terms of the needs of a particular type of film. Recently developed is a camera with an exposure meter built into it, so arranged that the iris

diaphragm is automatically opened or closed by a photocell to adjust to the correct value the light falling on the film from any scene. Thus the camera approaches the simplicity of the human eye, with its pupil which in dull surroundings dilates until its area is approximately ten times as great as when looking at a bright object.

The Land camera, introduced generally early in 1949, makes possible the production of a completed photographic print within a minute or so after the picture is snapped, and requires no external processing of negative or positive. The emulsions are provided sandwiched together on white paper, and a capsule of chemically treated salve is provided inside the film pack for the automatic development and fixing of each photograph. The mere act of pulling the film from the camera causes it to be developed and printed by a dry process which is very rapid, and which provides a finished print within one minute.

¶ 4

ORDINARY PHOTOGRAPHIC FILM is decidedly color blind. Not only does it fail to reproduce color, but it ignores any light whose waves are longer than those in the blue part of the spectrum, and fails entirely to respond to green, yellow, and red light. Such film will, however, record light waves too short to be seen, and hence can be used to take pictures with invisible ultra-violet light. This possibility of taking pictures with short-wave light has made practicable many new feats of microscopy and spectroscopy.

With a camera designed especially for ultra-violet photography, a whole new gamut of colors can be added to the ordi-

nary spectrum. These colors are, of course, invisible, and the film records them all in terms of black and white, but by means of the spectrograph they can be separated and made to serve various purposes. Since these short waves cannot penetrate glass, special lenses made of quartz, fluorite, or lithium fluoride must be used to focus them. Microscopes provided with such lenses, and using ultra-violet light, give the clearest pictures yet obtained of exceedingly small objects. Bacteria which are transparent to the eye must be stained to be seen properly in an ordinary microscope, but when ultra-violet light is used, the new invisible colors come into play, and the various parts of the creature stand out in vivid relief.

Ultra-violet photography is now widely used for detecting alterations in bank checks, in wills, and in other forged documents. Forgers who believed, from the evidence of their eyes, that their chemical or other erasing had wiped undesired writing cleanly from a piece of paper on which was a signature which they desired to use, have received a shock when confronted with the evidence of the camera. In such a photograph the original writing can usually be seen shining through that which the forger has applied to the supposedly blank surface. Bank notes are sometimes marked with invisible ink for future identification—ink which is invisible to human eyes, but which shines brightly when illuminated with ultra-violet light.

Fingerprints which cannot be made visible by ordinary methods can sometimes be detected by ultra-violet photography. To the eye a piece of paper may appear uniformly white, yet when a photograph is taken with short-wave light, smudges of various sorts appear. Perspiration, grease, white of egg, and many white powders are strongly colored in the ultra-

violet part of the spectrum, and hence appear darker than the surrounding paper, or in some cases brighter.

Other useful scientific tricks are possible when photog-

Incas, Pa., January 23, 1932.
This is my will made this day because I am not well. I give all of my property of all kinds to my friend, Jacob C. Grustig. He is to settle my estate and can either sell the house or keep it as it is. I do this for Jake because he is my best friend and has done so much for me.

Signed. L. V. Sarnoff Seal.

Incas, Pa., January 23, 1932.
Dear Jake This is my will made this day because I am not well. I give all of my property of all kinds to my friend, Jacob C. Grustig. He is to settle my estate and can either sell the house or keep it as it is. I do this for you Jake because he is my best friend and has done so much for me. He

Jan 4, 1932 Signed. L. V. Sarnoff Seal.

Courtesy of *Elbridge W. Stein*

Ordinary and ultra-violet photographs of a forged will. The original writing, except the signature, was effaced with chemical ink remover.

raphy is carried out with infra-red rays, whose waves are so long that the eye cannot see them. But to these waves, alas, ordinary film is blind—or was, until researchers, working to eliminate the blindness of film to green, yellow, and red light, found it possible to make film sensitive to a whole new gamut of colors beyond the visible spectrum, and nearly equal in extent to this.

Infra-red waves possess photons of relatively little energy and hence little ability to affect the photographic emulsion, but it was found that if a film was stained with any one of a number of dyes, the dye would absorb such light and use its energy to turn the emulsion black. The dye erythrosine sensitizes films to green and yellow light; emulsions treated with it are called ortho-chromatic. A mixture of cyanine dyes, when applied to the emulsion, makes it sensitive to red light as well, and film so sensitized is called panchromatic, because it responds to all colors. Panchromatic film is coming into increased use for all photographic purposes, as its red sensitivity is of great advantage for use with artificial light, which is unusually rich in red, and it gives pictures which look more natural than does ordinary film.

Step by step the discovery and synthesis of new dyes has proceeded in the research laboratories, until now dyes have been discovered which sensitize the film to waves as long as 12,000 Angstroms, twice as long as the shortest red waves. Even relatively cool objects emit these infra-red or radiant heat waves; and by employing an ordinary camera loaded with specially sensitized film, pictures can even be taken in the dark, using a hot flatiron as a light source.

Landscapes can be photographed in infra-red light with specially sensitized film, by using an ordinary camera fitted with a filter over its lens to remove all visible light. Shadows appear extremely black in infra-red photographs, as does the sky, while leaves, which reflect long waves well, are extremely white. If we could see infra-red light we would doubtless say that hills and meadows appear not green, but some new infra-red color, for the greenness results merely from the fact that leaves absorb red light, while our eyes see only the remainder of the visible spectrum.

The most important use of infra-red photography is to penetrate haze. A beam of ordinary light can traverse haze only a short distance; a beam of infra-red light can pierce the haze many times as far before the energies of its longer waves are dissipated. Obviously the way to see far on a hazy day is to use as long waves as possible, and infra-red photography makes possible the use of waves twice as long as those with which we see. From an airplane Major A. W. Stevens has taken many remarkable photographs of distant objects by using infra-red light; in one, Mt. Shasta looms up over the horizon from a distance of 330 miles, though absolutely invisible to the eye through a blanket of haze. Another remarkable infra-red photograph taken by Stevens clearly shows the curvature of the horizon 320 miles away.

Printing or writing on paper which has been charred in a fire so as to appear uniformly black all over is sometimes startlingly visible in photographs taken with infra-red light. The charred inked and plain surfaces, originally black and white, appear equally black in visible light, but in the new colors of the infra-red spectrum they appear different because they absorb infra-red light of various wavelengths differently. The penetrating infra-red rays will even go through certain kinds of black ink, and may show up underlying printing or writing that has been blotted out. Often old paintings can be judged best in terms of infra-red light, whose rays may penetrate surface layers of paint. A picture of a portion of the human body taken with infra-red light shows a complicated system of blood vessels and nerves lying under the relatively transparent skin.

Since long waves are so useful, would not longer waves be found even more useful? The answer is Yes, but certain natural limitations step in and prevent photography from being

extended to waves of much greater length. Every particle of matter, even in a piece of paper or in the wall of a room, is giving out heat rays of wavelength only slightly greater than those now photographable. If films are made sensitive to these waves of greater length, they must be kept and used always in a refrigerated enclosure. Otherwise even the paper around them would spoil them, for it would give out rays which in the sensitive state of the films would fog them like ordinary films wrapped in a sheet of luminous paper.

5

GEORGE EASTMAN BEGAN MAKING DRY PLATES in Rochester, New York, in 1880. Somewhat later he realized the desirability of producing plates that could be rolled up to keep out daylight, thus making possible the loading of cameras in daylight; and he first tried coating paper instead of glass with sensitive emulsion. The graininess of the paper made this unsatisfactory, so Eastman developed a "stripping film," in which the emulsion could be hardened and peeled from the paper before a print was made from it. Later he substituted cellulose nitrate for the paper, and with this new film loaded in a "Kodak," Eastman's trade name for the simplified camera he developed, picture-taking became practicable for millions of enthusiastic amateur photographers.

Motion pictures also were made possible by the invention of film. Though the courts have credited the Rev. Hannibal Goodwin with first successfully using a flexible cellulose nitrate film, Eastman was certainly one of those to whom the idea occurred independently, and he it was who, with this and many other photographic inventions, gradually built up

the largest photographic manufacturing establishment in the world. Today the company he founded produces more than ten thousand miles of motion picture film each month, together with acres of sensitive emulsions of other kinds, and supports a huge research laboratory from which have come many far-reaching photographic developments. From this laboratory and others like it have come most of the new emulsions which combine increased sensitivity with other desirable properties; all such firms credit much of their success to their research laboratories, which have contributed fundamental information on the nature of the photographic process.

Originally cellulose nitrate for motion picture film was coated with its sensitive emulsion on glass tables 200 feet long, placed in gloomy dark corridors. Now the film is made by automatic machines in almost endless sheets. The gelatinous syrup of silver salts, which when congealed will form the sensitive photographic surface, is coated on a sheet of film-base 40 inches wide at the rate of several feet per second. The sheet is heated and dried, and is then slit into tapes of the desired 35 mm. width, which are in turn perforated along their edges and stored in one- or two-thousand-foot rolls for shipment to Hollywood and elsewhere. The rooms in which such coating is done are probably the cleanest on earth, for no speck of dust can be allowed in the emulsion, where it might later appear as a scratch on a beautiful nose or in a lovely voice.

Ten million pounds of cotton is used yearly for producing cellulose nitrate for motion picture film. The thousands of tons of gelatin spread over this hold in emulsion silver salts which for their making require a million pounds of pure silver annually—one third of all the silver mined in the United States.

Motion pictures of the type made in Hollywood carry sixteen pictures on each foot of film, so each picture is necessarily small. In large theaters the screen may stretch across twenty feet of stage, and the pictures must be enlarged 250-fold on projection. This degree of magnification is sufficient to show graininess in each picture, but fortunately the images dance past so rapidly that the eye does not have time to dwell on such minor imperfections.

Although the film is moved rapidly through the projection machine, it must be standing absolutely still at all times that it is imaged on the screen. To achieve this end, a number of clever mechanical devices have been designed; these first pull a new picture into place while withholding all light from the screen, then project this picture for a few thousandths of a second, then darken the screen again, then project the picture again, and finally darken the screen while another picture is pulled into place. The intermediate darkening of the screen while the picture is in place and the double showing of each picture help greatly in reducing flicker. This entire cycle is repeated 24 times a second, so anyone who has spent two hours in the movies has been looking at 175,000 photographs.

Often it is desirable in scientific laboratories to photograph objects moving at very high speeds, and the time of each exposure must be made extremely short, whether for a "snapshot" or for motion pictures. To catch a glimpse of a golf ball being struck with a club, or to make the whirring of a humming-bird's wings appear to stop, no mere 24 pictures per second will serve—sometimes more than 1000 pictures must be taken in a second. No mechanical shutter can be asked to perform at this speed, and fragile film would tear if jerked ahead at such a pace. A better method is to make the expo-

sures in a darkened room, and to illuminate the subject with 1000 short, sharp, distinct flashes of very bright light. These flashes can be produced electrically, and the film can be drawn continuously through the camera at a high uniform speed, for so short are the flashes that the object seems to stand still during each flash. When a film exposed in this way is projected at ordinary speeds, time is greatly slowed down; the whirring of the humming-bird's wings changes to a pulsation slower than the majestic strokes of an eagle; the golf ball is seen compressed to half its normal thickness and then slowly springing back to normal. Using new types of electronic vacuum tubes which they have developed, Dr. Harold Edgerton and his collaborators have developed such high-speed photography to remarkable efficiency; and to its original use—observation of faults in high speed machinery—they have added applications in many other scientific fields.

An important advance in motion picture photography was its invasion of the home, where economy dictated new procedures. Large companies can well afford the three thousand dollars' worth of film which they must buy to make and distribute a single feature picture, but the amateur photographer requires something cheaper. Since he is satisfied with smaller pictures, less film is needed, so 16-mm. and 8-mm. widths were perfected for amateur use. One foot of 8-mm. film carries 80 pictures instead of the standard 16, runs through camera and projector one-fifth as fast and is less than one-fourth as wide. Therefore, on a strictly proportional basis, it should cost only one-twentieth as much per second of exposure as does the 35-mm. film. The 8-mm. film image is usually enlarged about 100 times on projection; if the size of the grains in the emulsion could be reduced still further, it could

be enlarged still more. Further research should make this possible.

The necessity of providing both a negative film and a positive copy of this film for projection long stood in the way of home motion pictures. To eliminate this need a clever process of "film reversal" was devised, with which any negative film can be converted directly into a positive during the development process.

In this process the exposures are made in the usual way, and the film is given ordinary development, but it is not then put into the usual hypo bath, which would dissolve out any silver salts which remained unexposed. It is put into a bath which leaves these unexposed salts, and instead dissolves out all the dark silver which has been deposited. Then the film is deliberately exposed all over to light, and is again developed. The areas which were originally light now turn dark, while those from which the silver had previously been removed remain light. The film is then fixed, and a positive image results. Most amateur motion picture film is now processed in this way.

¶ 6

BLACK SILVER, which has been deposited by light, paints so realistic a picture on white paper that we have learned to be satisfied with uncolored photographs, but a truly faithful color print is immeasurably superior to the best black-and-white print. The possibility of making photographs in natural colors has long interested scientists, but most methods suggested have been too complicated to be successful. Now several processes have been developed which give good results, and though no one has yet seen a truly faithful color photograph,

a few more years of scientific progress should bring improvements which will make the best efforts of today remind one of crayon enlargements.

The superiority of a natural color photograph arises not so much from the decorative effect of the colors as from the added detail which photography in color makes evident. A deep mass of autumn foliage, for example, which appeared of a uniformly dark tone in a black-and-white picture, might be resolved into a dozen greens and browns and reds when its true colors were photographed.

Offhand, color photography seems a very complicated business, for hundreds of tints and hues are found in nature, and it would appear that any process which could reproduce all of these must involve hundreds of dyes or pigments. Fortunately this is not the case, for colors are seen by the eye, after all, and the eye possesses only three color mechanisms. Any hue can be produced by a mixture of three primary color stimuli in varying proportions. Hence, if light which has come through a piece of red celluloid is mixed with light which has come through a piece of green celluloid, and with other light from a piece of blue celluloid, almost any desired color can be produced by mixing the beams of light in proper proportions. Certain colors cannot be reproduced quite perfectly, owing to physiological and psychological effects in the eye, but the deviation is not marked, and it can be shown that three primary colors will do quite as well as four or more.

As long ago as 1869 a French physicist, du Hauron, suggested a number of possible methods of producing color photographs, but though his ideas were good, science had not yet progressed to the point where they could be made practicable. Recently a number of his methods have been tried and found useful, and several new systems of color photog-

raphy based on them have been developed. Most of these are much too complicated for use in motion picture work, requiring as they would three cameras, three films, and three projectors, each operating with one of the primary colors: red, green, or blue.

Most successful for taking commercial motion pictures is the Technicolor process, into which have gone more than twenty years of research and development. Though this process is still being improved, its success is shown by the fact that more than fifty million feet of film a year are produced by Technicolor. Three separate negatives are taken through a single lens, but these are combined into a single positive film which can be projected like an ordinary black-and-white film, and hence requires no special apparatus in the theater.

A color process which is more complicated scientifically but simpler to use, is Kodachrome, developed in the Eastman Kodak Laboratories. In this process only one negative is needed, and by the reversal process this can be changed directly into a positive on development. The film itself is a triumph of scientific and technical skill, consisting as it does of five layers of gelatin filters and emulsions, piled together in a multiple photographic sandwich served on cellulose nitrate or acetate. Each gelatin layer is so very thin that the whole pile of emulsions is little thicker than ordinary film. Carefully arranged, one on the other, are an emulsion sensitive to red light, directly on the cellulose base; a layer of gelatin which lets through only red light; a green-sensitive emulsion, and a gelatin layer which lets through only green and red light; and a top coat of blue-sensitive emulsion. Light from the scene is sorted out by the various layers of dye into the primary colors, and these then enter and affect the appropriate emulsion layers.

Even more complicated is the development process which changes the negative into a positive. The final result, after four separate developments and a number of intermediate dyeing processes, is to give three sets of positive images in the one film; the upper image is yellow, the middle one magenta, and the lower one blue-green. When white light is shone through such a film the primary colors pass in the proportions required to reproduce the colors of the objects photographed.

Though the process is complicated, manufacture and development of the film is carried out by automatic machines which produce an extremely satisfactory product. A great advantage of the method is that the film can be used in ordinary cameras and projectors with no changes whatever. Some improvements in the exact colors and characters of the dyes used can be made, and when this is done, and the film becomes cheaper, a color process of this sort should entirely displace black-and-white motion picture film.

Snapshots in color, up until about 1942, had to be viewed by projection, but at last it has become possible to obtain prints directly in color. No matter how excellent a color photograph may be, when it is to be reproduced in a book or magazine the quality of the resulting picture is limited by the printer's selection of inks. For making colored pictures to mount in albums even this inferior process is too expensive, and the introduction of Kodacolor prints has filled a long-felt want.

In the early days of this century Edison dreamed of a machine which would record motion and sound and reproduce them simultaneously in full natural illusion. He stated his belief that grand opera would one day be given in the Metropolitan Opera House without any material change from the original, but with artists and musicians long since dead.

Though we have not yet reached the time when such illusion can be made complete, only a few further developments are needed to make it so. Of the five requirements—animation, sound, color, increased screen area, and the illusion of depth—the first three are now available in fairly satisfactory degree. Screen area can be increased when brighter projection lamps and films of smaller grain size become available, and depth can be provided by using stereoscopic projection. Several methods of providing the third dimension in motion pictures, by letting the two eyes see pictures photographed from slightly different angles, are in successful use. Some unpleasant effects remain, such as a habit close objects have of appearing transparent when viewed stereoscopically, and the considerable loss of light inherent in the viewing process, but these can be eliminated. This done, uncannily realistic forms of Lohengrin and Faust can walk the stage and fill the hall with voices no less real because their original producers have long since passed to dust.

A growth in the artistic standards of motion pictures is noticeable as technical methods improve. We can appreciate the artistry of a Titian or a Bach long after they have passed away; it is desirable that the art of a future Bernhardt or Paganini also should be enjoyable a century later. Scientific research, as it provides better film, brighter lamps, steadier images, clearer lenses, more natural colors, should enable musical and dramatic performance to achieve that permanence as art forms which hitherto they have only been able to envy their sister arts of writing, painting, sculpture, and musical composition.

XII

SIGHT CONQUERS SPACE

Your young men shall see visions.

Joel

MEN have long dreamed of being able to see each other though separated by hundreds of miles, and ever since the telephone was invented the layman has felt that if scientists could find ways of sending sounds over long wires, they should eventually be able to send sights as well. After all, one seeming impossibility appears no more difficult than another! Conquering space with vision is fundamentally a much more difficult problem than conquering it with hearing, however, and though for many years the public was led to believe that television was "just around the corner," new obstacles always arose before it arrived. Now that the major scientific hurdles have been crossed and regular programs are being broadcast, it hardly seems believable that television is here at last.

This television, newest of the practical contributions of physics which is destined to have wide social significance, is an infant not yet out of its swaddling clothes; but most of the problems which remain to be solved before it can grow lusty are economic rather than scientific. Anyone willing to pay for the privilege could now arrange to see clear around the world if he so desired, but few men could afford a glimpse so expensive.

In Europe, particularly in England, television was used more widely than in America before the war, a fact which appeared to indicate that European television workers had outstripped their American colleagues. Such is far from the case; American laboratories furnished more than their share of television developments, but government subsidies enabled European manufacturers to put the new toy into the hands of the public earlier, and the European public was more easily impressed with imperfect pictures. Television receivers had been on view in London department-store windows for several years before they appeared in America, and more than ten thousand sets had been sold in England, where a combination receiver for both sight and sound could be obtained for about three hundred and fifty dollars. Only later did similar sets appear in America.

It was not until 1948 that television really became big business, and that the radio and motion picture industries recognized that they were faced with serious competition in the field of home entertainment. During that year new transmission lines were put into operation which made it possible to send television programs from one city to another. Only very short radio waves can be used for television, and since these travel in straight lines instead of bending around the earth as do radio waves, it is necessary to launch them from a high eminence if they are to travel far, or to pipe them through special lines which are very expensive.

An experimental television transmitter of the Radio Corporation of America operated from the Empire State Building in New York City, for several years before World War II, but only after the war were regular broadcasts undertaken. Trucks equipped with television cameras are kept in readiness; these pick up sights and sounds from interesting events

and send them by ultra-short wave radio to their parent transmitter on the top of the highest building in the world; from these, pictures and sounds together are spread broadcast to the horizon. To make this possible has required continued effort over many years by a great number of eager, conscientious investigators and inventors.

2

SENDING PICTURES BY RADIO is fundamentally much more difficult than sending music, because the eye sees a myriad of details at one glance, while the ear can hear only a few sounds at a time, and these are all combined into a single sound wave. What the ear hears can be represented by a long wavy line of vibrations, like the groove in a phonograph record; what the eye sees requires a plane like a motion picture screen for its representation, and modern communication methods such as the telephone and the radio carry only a line of signals rather than a plane.

As early as 1875 a method of sending pictures over wires had been worked out, but the fundamental physical principles necessary to make it practicable had not then been discovered. The photo-electric cell had not yet been invented, and the only light-sensitive device available was the clumsy, slow, and unreliable selenium cell. One cell was needed to pick up each detail of the picture, and a separate wire was required to connect each cell to the distant receiver. Since cells and wires were expensive, the inventor contented himself with 64 of each, and the images sent were of necessity very simple. Few subjects would be available to an artist who could paint his pictures only by varying the brightness of 64 fixed dots.

In 1884 Nipkow suggested that any picture might be broken

up into a single long line of light, as a sweater may be unraveled into a long thread of yarn, by "scanning" it in narrow bands until its whole surface had been covered. His method, somewhat modified, is now used. The resulting line, after transportation in electrical form, is re-knit at the receiver into a single image.

Nipkow's scanning device eliminated the need for more than one transmission line, but a picture which is scanned in great detail gives a wavy line of extreme complexity because of the many variations of light and shade which it contains. To transmit a clear view of a tennis game, for example, at least 170,000 successive light variations are now used to present a single glimpse, and if 30 glimpses are sent in each second, as is now standard practice in television, 5,000,000 electrical vibrations must be produced in each second. Yet every detail of sound of the most complex symphony, played by a hundred-piece orchestra, can be conveyed by not more than 20,000 vibrations a second. This ratio of 5,000,000 to 20,000 is a rough measure of the relative difficulty of television and telephony.

True television should be distinguished from facsimile transmission, with which photographs are sent by telephone or radio for newspaper reproduction, for they are as different as motion pictures and "magic lantern" slides. Facsimile transmission is relatively simple, and has been widely used since 1925. The photograph to be transmitted, in the form of a transparent film, is wrapped around a drum on which it is rotated under a strong beam of light, which shines through it to a photo-electric cell. As darker and lighter portions of the film successively intercept the light beam, the phototube currents fall and rise, and these variations in current can be sent over long-distance telephone lines or by radio transmission.

At the receiving station the incoming currents operate a valve which brightens and dims a light shining on an unexposed film, and with this pulsating finger of light the picture is slowly traced out on the film, which is then developed. Or the impulses in the receiver may actuate a carbon-paper printing mechanism. With this device newspapers could be printed directly in the home during the night, but the system must be considerably improved before it can successfully compete with the boy who delivers the morning paper.

Contrast the twenty minutes needed for sending a telephoto picture, or the several hours available for printing a facsimile home newspaper, with the 1/30 of a second available for sending a television image. This speeding up by 36,000 times is what introduces the greatest difficulties of television. Radio transmission of motion pictures requires such high speeds also, but gives fewer lighting problems than true television, for the transparent film can be illuminated as brightly as desired, even to the point where it will almost catch fire. Far more difficult is the problem of televising a tennis match on a dull day, or transmitting a coronation from the dim recesses of Westminster Abbey by sight as well as by sound.

The invention of the phototube and of the electronic amplifier tube, and the development of wire- and radio-telephony, solved many of the early problems of television and kept a large body of inventors optimistically searching for means to solve the remaining problems. Many of the great electrical corporations established television research laboratories, and noteworthy advances came from the Bell Telephone Laboratories, the Farnsworth Television Laboratories, and the laboratories of the Radio Corporation of America, as well as from numerous smaller laboratories here and abroad. All the in-

ventors who had worked on the problem in the first half-century after the original crude television scheme was devised had used mechanical means, necessarily slow, to swing light beams or scan the image to be transmitted. The first really good solution of the problem appears to have been given by J. L. Baird in 1926, but even this had serious limitations. Such was the situation when Dr. Vladimir K. Zworykin became interested in television.

Zworykin, now director of electronics research in the RCA-Victor laboratories at Princeton, New Jersey, decided that if television were to become really practicable all moving mechanical parts must be eliminated and the problem carried down into the world of dancing electrons and atoms. Considering the amount of detail which must be carried to transmit an outdoor scene satisfactorily, and taking into account the meager light available on a dull day, he realized that only 60 electrons would be emitted by a phototube under the influence of the light from the brightest element of the scene; and these 60 electrons could not possibly control the output of a radio station with sufficient nicety.

If some device could be invented which would collect light from each spot all the time, instead of merely while the spot was being scanned, reasoned Zworykin, and would store the electrons thus set free against the time when that part of the picture was again scanned, 70,000 times as many electrons would be available—enough to control any radio transmitter. Here was a challenge to make a fundamental new invention —an invention which, to be realized, would need all the technique and finesse of which research in modern physics is capable. Zworykin mulled the problem over, reasoned out what needed to be done to solve it, tried many experiments, and, after several years of research, emerged triumphant with

a new type of "electric eye," the "Iconoscope." With this, television methods were revolutionized overnight.

¶ 3

THE ICONOSCOPE, OR "IMAGE SCANNER," which views a scene to be televised, is a large evacuated glass bulb at one side of which is mounted a screen on which an image of the scene can be formed by a lens. This screen is the equivalent of the film in an ordinary camera, but instead of being chemically sensitive to light it is electrically sensitive. It consists of a sheet of mica speckled with a mosaic of tiny silver globules coated with salts of caesium. Each globule is so minute that it cannot be seen with the naked eye, yet it will emit electrons into the vacuum of the tube whenever light falls on it. Whenever an image is thrown on the screen, all those globules on which light is falling emit electrons at a rate which depends on the light intensity, much as in a yard covered with tumblers of water each glass would lose water by evaporation at a rate which would depend on how much sunlight fell on it.

Opposite the screen in the Iconoscope tube is an "electron gun," a device containing a specially formed hot filament which is arranged to shoot a thin, intense pencil of electrons across the tube to the screen. Electric and magnetic controls are provided so that this electron beam can be played from side to side and up and down over the entire screen, much as a stream of water from a hose can be played by a fireman over the entire side of a building.

To develop the latent electrical image which is formed on the screen by the light, the electron stream is moved rapidly from side to side across the screen, slowly working upward

until electrons have been sprayed in turn into every globule. The electrons which the light has evaporated are thus replaced in each globule by the electron spray. The electric charge taken from the spray by each globule is a measure of how empty it was, and hence how much light had fallen on it.

To determine electrically the charge taken by each globule, a condenser plate is mounted behind the mica screen. Into this a tiny surge of electricity passes whenever a globule takes electrons from the beam, and these surges can be amplified with vacuum tubes to form variations in the current which controls a radio transmitting station. From signals thus sent the receiving station can reconstruct any image which falls on the Iconoscope screen.

The great advantage of this all-electric method is that each globule stores light for a long time between sweeps of the electron beam, instead of having to decide how much light there is as soon as light strikes it. Theoretically the Iconoscope method should be 70,000 times as sensitive to light as previous methods, but actually it is only about 10 per cent efficient, so the gain falls to approximately 7000 times—still enough to make the difference between failure and success.

The electron beam of the Iconoscope fingers the image on its way across the screen much as a blind man might feel a bas-relief by drawing his finger across it. The more slender the finger and the more times it is drawn across the relief, the greater the number of details perceived. Early television outfits crossed each picture only twenty or thirty times, but with the Iconoscope the number has been increased until now 441 crossings is standard and 567 is considered possible. Each time the electron beam hurries once across the picture it sends out at least 441 current variations, and it must do this 441 times

to cover the screen once. Since it must cover the screen 30 times in a second if no flicker or ripple is to be noticeable in the pictures, 5,000,000 current variations must go out every second.

The Iconoscope is now familiarly called an "ike" by the technicians who have long referred to a microphone as a "mike." It converts light into electrical signals much as a microphone converts sound into electrical signals. "Mike" listens while "Ike" looks, and together they translate the impulses which they pick up in the television studio—or out of doors—into pulsating currents which can be sent over wires.

A standard Iconoscope can now "see" scenes which are lighted only one-tenth as brightly as would be required for photography with a motion picture camera, and it is expected that new Iconoscopes will be able even to send pictures of events occurring in a room which appears only dimly lighted to the eye. Of greater interest to scientists is the fact that the Iconoscope is sensitive to invisible infra-red and ultra-violet rays, and hence holds promise of furnishing an eye for super-microscopes and for haze-penetrating super-telescopes—an eye for such purposes more perfect than the human eye itself.

4

In the television receiver the incoming electrical signals are reproduced as pictures on a small screen. A mass of tiny lamps might serve for such a screen, if each lamp were able to brighten or dim as rapidly as the electrical signal dictates whether the part of the screen the lamp occupies is to be bright or dark. Tiny gas-filled lamps similar to the large lamps used in neon advertising signs were tried for this purpose, but

so many were needed for a single screen that the system was hardly practicable.

The problem was finally solved by making use of the cathode-ray oscillograph, that electronic vacuum tube which has for so long been used to translate into visible form rapid changes in electric currents. In its dressed-up television form, this tube is known as the "Kinescope," or "motion viewer"; and such a tube forms the heart of almost every modern television receiver.

The Kinescope is a long funnel-shaped vacuum tube of glass, in one end of which is an electron gun similar to that in the Iconoscope. This gun shoots its electron beam against a screen which covers the large end of the tube. The screen is formed by painting the glass of the tube with a crystalline powder made from a material which glows strongly with light when struck by electrons. Billions of electrons are shot down the tube in a narrow pencil at speeds greater than 20,000 miles a second, and this tenuous electric spray can be played from side to side and up and down, like that in the Iconoscope. The electrons themselves are invisible, but wherever they splash against the fluorescent screen a tiny bright spot of light appears. If now the beam be vibrated from side to side so rapidly that the eye cannot follow the spot, a streak of light will be seen. Ten thousand such streaks can be produced in a second if need be, and if 441 are laid side by side so as to cover every part of the screen, this appears covered with a uniform glow.

Now the electron brush can be used to paint a television picture. By means of an electric valve the number of electrons in the beam can be adjusted instantly to any desired value, and thus the brightness of any part of the screen can be controlled. The Kinescope beam is kept zigzagging across its

screen in exact synchronism with the motion of the Iconoscope beam over *its* screen; and the signals from the Iconoscope, as it feels variations in the intensity of light in the image which it is scanning, increase and decrease the flow of electrons in the Kinescope and hence the brightness of the Kinescope spot. In a few years it should be commonplace for a million Kinescope beams to be rapidly feeling their way across a million screens, in blind obedience to impulses from one master Iconoscope in some broadcasting station.

Many research problems had to be solved before this high-speed process of using electrons to paint in light became practicable. To produce a clear picture the electron beam must be as sharply pointed as a Chinese writer's brush, and this is possible only if the tube is so well evacuated that of every ten billion air molecules originally in it not more than one remains. Only the most modern air pumps can produce so perfect a vacuum; and while they are pumping, the tube must be heated almost red hot to drive out molecules of air and water which may be imbedded in its glass or metal parts.

At first it was found difficult to get fluorescent screen materials which would emit light of sufficient brightness when struck by electrons, so intensive research was started in several laboratories to find more responsive powders. Those which fluoresced most brightly unfortunately emitted green light, so that a black-and-green picture was seen on the screen instead of the more desirable black-and-white. However, after many fluorescent substances had been tried and hundreds of new materials had been mixed, crystals which would give yellow light were found; then red, blue, and other colors were added to those available, and ultimately fluorescent powders which would flash out brilliantly in almost any desired color were produced. By mixing proper proportions of suitable blue- and

yellow-fluorescing powders, it is possible to produce light which appears white, and thus television pictures in black and white became feasible.

While some progress was being made in improving color, however, other difficulties crept in. It was found, for example, that many fluorescent substances were phosphorescent as well; they would start giving light immediately on being struck by electrons, and would continue to do so for some time afterwards. When a tennis ball was seen moving across a television screen coated with such a material, the ball appeared to have a tail like a comet, as the light slowly died away behind it. When this effect had been eliminated entirely, it was found advantageous to have the light linger slightly before going out, to help eliminate flicker from the screen. Phosphors were eventually found which produced light lasting about 1/30 of a second, one picture fading from the screen just before the next appeared on it.

The powder used to coat early television screens gradually grew tired of emitting light, so that after such a screen had been in use for a few hours it gave less and less light, even though struck as forcibly by the electron beam. Again research produced the answer; a zinc ortho-silicate phosphor was found which could be struck so hard by electrons as to be made almost red hot, yet it would continue to emit light with undiminished fervor, and even after 1200 hours of use showed a full three-quarters of its original vigor.

The larger the screen of a television receiver, the more light must it emit if the picture on it is to appear satisfactorily bright. For use in a small room a tube of nine-inch diameter will serve, though its screen is not much larger than an average photographic portrait. Tubes almost two feet in diameter have been put into commercial use, but as the screen is made

larger the engineering problems of controlling the tube increase at an alarming rate. One RCA-Victor engineer has constructed a tube with a screen almost three feet across, but the glass at the screen end had to be made two inches thick and was carefully bulged out so that it would not collapse under the force of more than five tons exerted on it by the atmosphere.

A wiser plan than to attempt to build larger tubes is to throw on a motion picture screen a magnified image of what appears on the screen of a small tube. This can be done only if the image is made intensely bright, but some of the newly developed screen materials make this possible. Electrons can be hurled across the tube at the screen by 18,000 volts; and by using a tiny electron spot the diameter of a hair, it is found possible to project pictures of a size and brightness almost to equal the 16-mm. motion pictures used for home projection.

Materials to give still brighter television images can and will be produced. This need has stimulated a renewed interest in research on fluorescence and phosphorescence, and not only have many new practical results been achieved, but for the first time physicists have succeeded in understanding why some substances emit fluorescent light while others do not. To reach this understanding it has been found necessary to apply the quantum theory of atomic structure to the problem; television, like so many other advances, rests directly on atom-smashing.

¶ 5

IN THE TELEVISION TRANSMITTING STUDIO, where sights and sounds are to be translated into electrical signals, and in the

home receiver, where these signals are to be reproduced as sights and sounds, few scientific problems remain unsolved. Less satisfactorily answered, however, is the question, How are the electrical signals to be carried from sender to receiver? On radio waves, to be sure; but what kind of radio waves? To attempt to carry a television program on the radio waves used for ordinary broadcasting is like attempting to carry the roof of a house on a bicycle ridden along a narrow path through the woods.

When a steady stream of electromagnetic waves is sent out from a broadcasting station, all the waves are of exactly the same length. But when speech or music is being carried by these waves some of the waves are shortened and others are lengthened, and in the receiver these waves of changed length may become entangled with signals from some other station broadcasting shorter or longer waves. To avoid such interference of signals, radio stations are assigned wavelengths which differ in frequency by at least 10,000 vibrations a second (10 kilocycles), twice the frequency range within which most sounds are comprised.

. Television signals, with their greater wealth of detail, cause any waves carrying them to interfere with waves from neighboring stations when the two are tuned to frequencies which differ by less than five million cycles. The band of frequencies required to broadcast a television program is so wide that, if ordinary radio waves were to be used, only one television station could be operated at a time, and all other radio activities would have to be shut down. In fact, there is not room for even one television station in the band of the electromagnetic wave spectrum which is used for radio-telephony and telegraphy.

Between 600 kilocycles and 1500 kilocycles (500 to 200

meters wavelength, the standard broadcast range) there is a range of 900 kilocycles, which will accommodate 90 radio-telephone stations spaced 10 kilocycles apart. But consider waves only one-tenth as long, from 50 to 20 meters; since these vibrate ten times as fast their frequencies lie between 6000 kilocycles and 15,000 kilocycles, giving a ten-fold greater range of 9000 kilocycles. This range is almost great enough to accommodate two television stations, but this part of the electromagnetic wave spectrum is already pre-empted for short-wave radio-telephony. If we decrease the wavelength by another factor of 10, considering now the range 5 meters to 2 meters, we find a range of 90,000 kilocycles, or enough to accommodate 18 television stations without interference. The problem is therefore solved if ultra-short waves can be used.

Now, however, new difficulties arise, for such ultra-short waves do not follow the curvature of the earth like their longer companions, nor are they nicely reflected from mirrors in the stratosphere such as keep ordinary short waves from bounding away from the earth. Instead, they travel in straight lines like beams from a searchlight.

Little is yet known about all the properties of very short radio waves. One scientist of the Radio Corporation of America spent days hovering in an autogyro about the Empire State Building, like a bumblebee over some gigantic hollyhock. The nectar he sought was information regarding the strength of the television signals at different elevations and in various directions around the broadcasting antenna. In the cockpit of his autogyro he carried delicate measuring instruments, and with these he determined the power which a television receiver would find available if placed in any specified location. When a skyscraper loomed between his hovering

laboratory and the transmitter, he found that it cast long deep shadows if waves shorter than about 10 feet (3.5 meters) were being used.

With a television transmitter in its tower the Empire State Building becomes a 1300-foot Statue of Liberty, from whose torch radiate waves ten million times as long as those of light. Two kinds of waves are in fact being broadcast: waves ten million times as long as those of red light carry messages for the eye; and waves ten million times as long as those of blue light carry messages for the ear.

Originally it was thought that if television programs were to be transmitted from New York to Boston, for example, it would be necessary to send them via intermediate relay stations, each of which was visible from the next. Where high mountains were available these could conveniently be used to support the relay towers, but in level country, it was suggested, airplanes, helicopters, or balloons could be made to serve. As matters worked out, it became possible to avoid the necessity of insuring that a straight line connecting pick-up station and final broadcast antenna should not strike the bulging shoulder of the earth between.

Fortunately radio waves can be sent over wires and thus can be piped around corners, and though ordinary long-distance telephone lines could no more accommodate a bulging television program than an ostrich can swallow a wash tub, special coaxial cables—copper wire stretched inside copper pipe—can be used to accommodate the wide range of frequencies necessary. Though such a cable is taxed to its capacity for television, it is in fact a very broad electrical highway, for if broad enough for one television program it could be used comfortably to carry 500 simultaneous telephone conversations or 6000 simultaneous telegrams. Such

lines, though expensive, are being built to carry television programs from one city to another, and at the end of the line the programs are broadcast on ultra-short radio waves.

Much promise is held for special copper-tube cables along which can be sent waves only a few inches long; such micro-waves lie in a world now being actively explored. The greatest need at present is new methods for producing such waves, new sensitive tubes with which to amplify them, new measuring devices to record and observe them. To ask scientists to study such a new, untried region is like asking a boy who is whistling his highest note to learn to whistle a tone ten times higher in pitch. The first of his problems would be to obtain a new set of ears with which he could hear so piercing a note. During the war years much progress was made with micro-waves, especially for the development of radar.

❡ 6

TELEVISION RECEIVERS EXTRACT FROM THE ETHER, by means of a single antenna, waves carrying both sight and sound. Inside the receiver the signals are separated and amplified, those carrying vision going to the television Kinescope, those carrying sound going to an ordinary short-wave radio receiver and loud-speaker. In some television sets the Kinescope screen is set into the front of a cabinet much like that of an ordinary radio receiver. In others the screen is mounted horizontally in the top of the cabinet; when the lid of the cabinet is raised to an inclined position the screen can be seen reflected in a mirror. This device shields the screen from the direct light of the room and gives clearer pictures.

The equipment needed for receiving sight is little more bulky than that needed for sound, and since most cabinet-

model radio receivers contain much unused space, television receivers could be incorporated into current radio cabinets. Increasingly common is a cabinet containing a television receiver, a phonograph, and a long- and short-wave radio receiver, all engineered to give a unified type of response.

It seems unlikely that television will ever compete seriously with motion pictures—the latter carry sights and sounds across time as well as through space. The two techniques should be of mutual aid, and as phonograph records are widely used in radio broadcasting, so motion picture films are forming the basis of many television programs.

Television, in contrast to the experience of the motion picture industry, found its voice awaiting it at birth. But what of the other prerequisites of naturalness which the motion picture is now slowly acquiring—natural color and the illusion of depth?

Television images can readily be produced in natural colors; this problem merely presents three times the difficulty of television in black and white, but with present-day limitations in band width this is difficulty aplenty. The problem reduces in essence to transmitting three times as much detail as is needed for black-and-white television, for every scene must be depicted in three colors—red, green, and blue. At present too many other more important needs intervene, but scientifically there is no apparent reason why television in full natural color should not some day be available.

Again, perception of depth can be introduced by using methods of stereoscopic projection which are already well worked out. Two sets of images could be transmitted to produce an effect similar to that of an animated stereopticon—interesting, but at present hardly worth the trouble involved.

XIII

THE CAPTURE OF MELODY

Empires dissolve and peoples disappear,
Song passes not away.

WILLIAM WATSON

CARUSO sang and died just twenty years too soon. Phonograph records of his voice are available, but such scratchy, distorted reproduction gives only a hint of the original and leaves quite unreported its true fullness and grandeur. The Caruso of a decade hence should fare better, for sound reproduction has been improved to a point where practical perfection is quite within reach. Nor is this a loosely defined perfection, but one whereby anyone should be able to speak or sing or play, and then, at the push of a button, have the entire performance repeated once or a hundred times, so faithfully that no ear could distinguish between original and reproduction.

Few achievements of science could in pre-view have appeared more magical than the possibility that the lilt of a song or the fire of an oration, both so obviously fleeting and disembodied, could be preserved and then reproduced a day or a century later. The very conception of imprisoning sounds and later releasing them required a bold imagination, and the idea that this was a possibility was, in fact, grasped only piecemeal. Even after the original "talking machine" was constructed by Edison in 1875, many years were required to de-

velop the recording of music to the point where it could be appreciated for its merits more than for the fact that its very existence was remarkable.

The electric phonograph and the talking motion picture that we know are far from perfect in their re-creation of sound, but this limitation now arises almost entirely from the high cost of the apparatus needed to achieve perfect results. After years of investigation, applied physicists have learned how to construct devices which can store and repeat the most complex sounds with true fidelity, but sound-engineers are still handicapped by the practical necessities of low-cost equipment. Perfectly faithful reproducing devices should eventually be as commonly available as imperfect ones are today.

Grown long accustomed to the scratchy futility of the mechanical phonograph, the world is only slowly realizing the possibilities of more perfect sound reproduction. The term "phonograph record" has come to suggest limitations in regard to the quality of music similar to those that the term "cold storage" suggests in regard to the quality of eggs; yet neither limitation is inherent in the method of preservation. Radio broadcasters often go to amusing lengths to avoid prejudicing listeners against their scientifically reproduced music. By law this must be announced for what it is, even though an increasing proportion of recorded programs cannot be distinguished from originals over the radio; and so we hear frequent mention of "recordings" and "transcriptions," but little of "phonograph records." Actually the new records are made differently and bear little resemblance in quality to records made before 1930.

As recorded and broadcast music have improved in quality they have been responsible for a surprisingly widened interest

in all music, both popular and classical, and a greatly increased appreciation of it. Eminent musicians agree as to the magnitude of the musical revival which followed the first decade of radio broadcasting and improved sound recording. A few years ago musicians feared that after the radio had killed the phonograph, as it seemed to be doing, the radio and the talking motion picture would together practically eliminate personal musical endeavor. Quite the reverse happened, for the radio and the telephone together first proceeded to revive the phonograph industry by presenting it with improved methods of recording and an impetus to develop these further by means of scientific research, and then all three led to a surge of musical appreciation such as the world had never before seen.

The pessimists who had predicted that the influx of mechanical music into the theater and the home would eliminate personal musical performance were proved entirely wrong, for sales of sheet music and of musical instruments rose to new heights as the quantity of reproduced music increased and its quality improved. Interest in school orchestras and choruses was made to flourish as never before, and members of the musicians' unions, who resented the intrusion of machine-made melody, found, as happened in so many other cases of apparent technological unemployment, that once the initial dislocation had been adjusted the advent of reproduced music proved to have helped rather than hindered their advancement.

There appear to be vast possibilities in the development of a new field of musical participation for the amateur, lying midway between listening to an expert performance, or to its reproduction, and aspiring (but less often inspiring) personal participation. All musical techniques and the design of musi-

cal instruments rest on a basis of science; and science has much more to offer than the array of personal-performance instruments—saxophones, trumpets, and fiddles—on the one hand, and phonographs, radios, and talking movies on the other. Though the electric organ is a step in the intermediate direction, it is but a short one.

Stretch four gut strings along a bent stick, and rub them with a taut hank of resined horse-hair, and the acoustical results are unimpressive. But replace the stick with a curved wooden box of peculiar design (all the better if it happens to have been fashioned by a man named Stradivarius), and let the rubbing be done by a Kreisler, and what a difference in results! A human ear will appreciate the distinction between the two types of sound produced, but its owner cannot suggest what to do to improve the less pleasing sound. A physicist, with his microphone (or electric ear) and oscillograph (or magic eye), can study the form of the sound waves produced in each case, and can tell how they differ, but thus far he has done almost nothing to make them alike. There seems to be no reason, however, why instruments of varied sorts cannot be designed in which tone quality, so difficult for the beginner to control, is pre-fabricated—ready-made yet adjustable. This has, of course, already been done to a limited degree in the piano, which probably explains to some extent the popularity of this instrument. But is it too much to envisage a future in which the strains of "Humoresque," filtering through the walls from the daily violin practice of the neighbors' Willy, are obviously implemented with rhythm, melody, and expression which are Willy's own, but with tones which are as vibrant and alive as they were the day Jascha Heifetz originally gave them their wave-form? As Willy progresses through his years of practicing,

his interest is then pulled ahead by the sonorous strains which emanate from his scientific fiddle, instead of being dulled by the squeaks which so discouraged a previous generation. Adjustment of a knob by his teacher can be made gradually to decrease the Heifetz contribution to the output, and Willy eventually stands or falls on his own harmonics. Whether or no such visions are desirable artistically, scientifically they are capable of realization.

A beginning has already been made in using the phonograph as an accompanying instrument. The amateur pianist, with a modern reproducer and suitable records from which the piano part has been omitted, can in his own home dash into a concerto accompanied by Toscanini and a great symphony orchestra quite as readily as if he were Harold Bauer himself, and with much less effort on the part of the conductor. Some care is needed in tuning record to piano, and to make this tuning easier special stroboscope disks, disks of paper on which recurring designs are printed, can be obtained. If such a disk is placed on the record so as to turn with it, and is viewed in the light of a small flickering lamp, the pattern on the disk will appear to stand still when the speed of the phonograph is correctly adjusted. Then record and piano will harmonize if the piano be kept tuned to the standard pitch used by the great orchestras. Even if the piano be slightly off pitch the adjustment of the phonograph can be made by ear.

At least one scientist with a musical bent, who possesses a home sound recorder, has gone so far as to play string quartets with himself. He first plays and records the cello part. Then he plays the resulting record through on a reproducer while he accompanies its playing with another part, say that of the viola. The second record is then played while he

records it together with his rendition of the second violin part, and so again until all the parts of the quartet have been accumulated. If the quality of recording can be made such that the music does not lose appreciably by successive re-recordings, the only limitation on any performer who wishes to make a full orchestral rendition by himself should be his own virtuosity.

12

THE HUMAN MIND grasped only slowly the idea that melody can be caught, preserved, and later released in its original freshness. First it was necessary to learn the characteristics of sound waves. An acoustical observation which probably aroused human curiosity at an early date was the rattle which emanates from certain objects when loud sounds of a suitable pitch are produced near them. Certainly such resonance had been noted in Biblical days, whether the fall of the walls of Jericho under the impact of sound from Joshua's trumpets can be ascribed to this cause or not. Early observers must also have noticed that a thin sheet of paper-like material when held in the hand can be set into perceptible vibration by singing loudly against it. But it was only during the last century that any known experimenter fastened a light straw pointer to the center of a paper diaphragm and saw the vibratory motion produced by a sound wave magnified when he watched the end of this pointer. Later some clever physicist deposited a delicate layer of smoke on a piece of glass, which he then moved transversely in contact with the end of the vibrating straw. Thus he forced the sound waves to trace a wavy line whose shape was found to be characteristic of the sound heard.

The line so traced by the straw soon revealed many secrets of sound, and surprisingly simple secrets they turned out to be. The higher the pitch of the sound, the closer together were crowded the wiggles in the wavy line, and when the sound became louder the waves spread wider in amplitude. If several sounds arrived at once, as when a chord was played on the piano, the straw did not trace several wavy lines, but only one, which was merely more complex and intricately curving than that produced by a single tone. This ability of a single line to carry a multiple sound turned out to be most important, for the possibility of reproducing sounds with any reasonably simple apparatus exists only because the tones from all the instruments of even the largest symphony orchestra will blend into a single air wave whose form can be represented by one wavy line. The more complex the sound, the more waves crowd into a given length of line; but anyone who can control such sound lines has in his hands dominion over all there is to speech, music, or any other kind of sound.

That a single sound line must result no matter how many separate sounds combine to produce it is obvious when we realize that points on the wavy line represent positions of a point on the eardrum of anyone who hears the sound; and an eardrum, no matter how rapidly it vibrates, can hardly be in two places at once.

The loudness of a sound depends on the energy carried by its waves. One cannot readily discuss loudness without talking about decibels, and the term is appearing increasingly in the newspapers as the public becomes more noise-conscious. The decibel is a weird sort of logarithmic unit, but once understood its use makes discussion clearer. Imagine a sound just loud enough to be heard—the rustle of a leaf on a calm June morning in the woods. A sound ten times as loud as this is said

to have an intensity of one bel. A sound ten times as loud as *this* is of intensity two bels, and for each ten-fold increase in intensity another bel is added. One tenth of a bel is called a decibel, so if a sound is one million (10^6) times as intense as the least we can hear, we need only refer to its intensity as 6 bels, or 60 decibels. Thus when a physicist announced that the noisiest place in New York City which he could find was the corner of 34th Street and 6th Avenue, and said that the noise there was of intensity 90 decibels, he meant that it was about one billion times as intense as the least sound one could hear. Even the applause given the various members of the royal family of Great Britain when they appeared on the palace balcony after the coronation of George VI was reported by the press in these units, the Queen Mother being said to have topped the lot with 75 decibels.

Because the ear is so sensitive, 75 decibels of sound actually represents very little energy. In fact, the loudest orator cannot with his own unaided lungs radiate more than one watt of power, and if he kept at it day and night for a month his emitted energy would, if converted into useful electrical form, be worth but three cents. So minute are the amounts of energy carried by sound waves that the cost of the power which operates a loud-speaker is almost negligible. But this very fact makes all the more difficult the recording of sound, for even loud sounds have little energy with which to push the diaphragm of a microphone which is to record their wave form. Only an accident of genius could have demonstrated in the days before vacuum tubes that sound waves can be caught, stored, and reproduced.

Thomas A. Edison once constructed a toy in which a funnel was used to concentrate sound waves, which would then rattle a piece of paper held against the funnel. A light figure

of cardboard was arranged so that when one said "Saw wood!" (or anything else) into the funnel the vibrations moved a tiny saw back and forth, and by talking long enough one could cut a toothpick in half. At about this same time Edison had been recording telegraph signals on a revolving disk, and these signals made a humming noise whose pitch, he noticed, depended on how fast the disk was turning.

Observing these two devices gave Edison the idea that sound might be reproduced if the wavy line which a sound wave had produced could be persuaded to re-create an air wave in its own image. Once the wavy line was captured, why not let it move a light membrane or diaphragm which would push and pull the air and make this vibrate in synchronism with the wavy line? There was no flaw in this reasoning and a year or two sufficed to show that the idea was practicable, but sixty years more and the work of many men were required to bring it within reach of perfection. Edison gave the phonograph its voice, but hundreds of scientists were required to teach it how to sing acceptably.

At first Edison had no idea of reproducing music. He wanted to re-create the sounds of speech, so he called his invention a "talking machine." By shouting into a horn while he turned a tinfoil-coated cylinder under a needle fastened to a diaphragm, Edison was able to make the instrument, when the cylinder was again rotated under the needle, faintly croak back "Mary had a little lamb," which thereby became again immortalized among famous first lines.

Edison decided that his invention could best be used as a dictating machine. Others thought that phonograph records might take the place of books, and that sending word-of-mouth messages in parcels might prove more convenient than letter writing. The dictating machine has achieved a notable

place in business and industry, but the ability of a record to reproduce melody has completely overshadowed its ability at speech recording.

The distorted output of the horned phonographs of 1910 and earlier was such that much of the interest in "canned" music was aroused by wonder at being able to recognize at all the words and tunes which came from an inanimate box. Even as late as 1920 the listener was still interested in how life-like were the outpourings from a record, but by 1935 so great was the improvement in sound reproduction that his concern had switched to criticizing departures from perfection.

The limitation of the pre-1925 phonograph was that mechanically the job of sound reproduction was just too much for it. The groove on the record, in which is carried the wavy line which stores the sound pattern, is usually only six thousandths of an inch wide and a third as deep. Measurements with the cathode-ray oscillograph, the modern vacuum-tube successor to the vibrating straw, show that complex sounds can be satisfactorily reproduced only if the wavy line can be made to keep its shape even when it is forcing the phonograph needle to vibrate as few as fifty times in a second, or as many as ten thousand. The more rapidly the needle and its diaphragm are forced to vibrate, the more they tend to cut corners. If the needle deviates from its proper position by one thousandth of the width of a hair while the record is racing under it, whether in engraving the groove or later in picking up vibrations from it, the volume of the high tones may be double what they should be, or absent entirely, and a beautiful soprano trill may become a screech or a whisper.

If we were willing to use records the size of a cartwheel, which would play through in only four minutes, we could use

a groove wide and deep enough to move a more powerful needle, and might expect to reproduce music more faithfully by means entirely mechanical, although certain inherent limitations would remain. But if records are to be kept small and convenient the phonograph must always suffer from laryngitis unless it is cured with the aid of electricity.

Vacuum-tube amplifiers turned out to be the key to the situation, for they made it no longer necessary for the sound waves to waste their limited energies cutting wax. The waves need only govern the amplifier which controlled the shape of the groove they wished cut, and obedient electricity would furnish greatly increased power to the cutting-needle. Again, when the record was being played, the energy radiated as sound could be increased many fold by first converting the motion of the needle into electrical vibrations, which could then be amplified with vacuum tubes, just as the voice currents are amplified in a long-distance telephone receiver or in a radio set.

3

A MODERN SOUND RECORDING STUDIO closely resembles a radio broadcasting studio, as well it may, for both are first concerned with capturing sound waves and changing them into equivalent electrical form. The sound to be recorded is caught by a microphone, which must be of much higher quality than is required for telephony, since music sets more rigid requirements than speech. No ordinary telephone transmitter is faithful enough for this purpose, but since workers in the telephone research laboratories have studied the control and measurement of sound waves and their transformation into electrical form more carefully than anyone else, it is not sur-

prising that the physicist who devised the first high-fidelity microphone, Dr. E. C. Wente, was a member of the telephone research laboratories. Other types of high-fidelity microphones have since been developed, but all require the assistance of the vacuum-tube amplifier to bring their electrical output up to usable strength.

When sound is to be recorded, the amplified current from the microphone is fed to the coil of a magnet, which wiggles a tiny chisel designed to engrave, while vibrating at a rate which occasionally rises to 10,000 times a second, the moving surface of a disk whirling under it. The miniature plow which thus traces a musical furrow may be pointed with a sapphire or a diamond, and must be critically adjusted to cut to exactly the proper depth. A diminutive silent vacuum cleaner is used to suck up the long thread-like shavings which are dug from the disk so that these will not interfere with the smooth cutting of the next furrow.

The wiggly groove thus cut must conform to the proper shape of the sound track within a few millionths of an inch, and it must therefore be engraved on a surface which is as flat and smooth as a mirror. Thin films of wax spread on thick metal plates, or polished cakes of special soap over an inch thick, are used. (This soap, which is firm yet soft enough to be cut with an engraving needle, would hardly be suitable for cleansing purposes, yet it is real soap nevertheless.) If this original record were to be played on an ordinary phonograph it would be damaged by the great pressure with which the sharp needle would dig into its soft surface. Records which are to be played repeatedly must be made of harder stuff, and a complicated process of reproduction is needed to transfer the original groove form to the thousands of commercial records which are to carry it.

Any tiniest change in the shape of the sound-groove during this reproducing process will cause the re-created sound to differ from the original. Scratches or dust marks will be heard as noise; rounding of corners on the wave patterns will cause the sound to be unnatural and distorted. Only the painstaking methods of the research laboratory could have made possible the delicate control required for so intricate a process.

The first step is to coat the original record with gold, which usually is done by electroplating. An old method of gilding which is again coming into favor involves putting the record in an evacuated glass container where gold atoms can be sprayed over it electrically until a thin gold layer is built up. This layer of gold is then strengthened by plating it with copper until it can be stripped from the record as a metal shell on which the sound-grooves stand out in golden relief. This shell is then used as a negative mold from which positive metal duplicates can be made, and these in turn are used to produce the chromium-coated stamping negatives which serve to press the final records by the hundreds from warm soft dough.

Before each record-press stands a young woman, at her side a flat hot-plate on which rectangular slabs of dough, made from shellac mixed with clay and other materials, are kept soft and pliable. When the press opens she inserts a mass of this dough between the two chromium-plated record molds which carry the replicas of the wavy lines of sound on their surfaces, closes the jaws of the press, and releases a force of over sixty tons which squeezes the mass into a thin disk, impressing on its upper and lower surfaces the sound-track grooves from the master records. A moment later a spurt of water cools the press internally, its jaws open, and the operator takes from

the mold a completed disk record, ready, after its rim has been burnished, to be played.

The sight of hundreds of steam-heated presses stamping out phonograph records is likely to give rise to that exaltation which is occasionally felt on viewing one of man's accomplishments in fashioning nature to his ends. At one moment we see a mass of dough; thirty seconds later it emerges from the press transformed—the Prelude to *Lohengrin!* Not the least wonder of science is its ability to convert shellac—excreted by an insect—into a vehicle for profound emotional experience.

Most records of the type played in the home are made from shellac mixed with coloring materials, with clay or some other filler material added to give hardness. The particles of filler add somewhat to the background noise, but something of the sort is necessary to keep the needle from cutting the soft shellac. If a fresh steel or fiber needle is set on a record it may not fit the sound groove, but a single turn of the disk will shape the needle so that its pressure soon falls to normal. Needle-scratch, coupled with distortion of the sound, has always in the past betrayed the phonographic source of reproduced music.

Record materials must be extremely pure and free from fine particles if background noise is to be eliminated. When the noise problem was first attacked scientifically, two years of research resulted in the reduction of needle-scratch to one-fourth of its previous loudness. Now this rasping annoyance has been completely removed in the best apparatus and is being eliminated rapidly from records of cheaper grade.

Seldom has chemistry come more importantly to the aid of physics in industry than by the provision of new substances to hold the sound-track. Shellac is still widely used because

of its cheapness, but new plastic materials, such as vinylite, which are less brittle than shellac, which carry music better, and which produce less scratch, are being increasingly used. Use of these materials results in great saving of space and decrease of breakage for commercial recording and for other purposes where expense is less important than it is in the home. In broadcasting studios it is not unusual to see great musical disks half again as big as an ordinary record but only one-third as thick, so flexible and tough that they can be bent nearly double without breaking. Since sound is stored only on the surfaces of a disk, the thinner this can be made the less volume of matter will be required to hold a given period of melody. An ordinary suitcase, which might be filled by enough cylindrical records to play for three hours, would hold at least 100 hours of speech or music packed on disks. Some modern records are hardly thicker than a sheet of manila paper, and paper itself, coated on both sides with resinous materials which can be softened while the groove is being pressed, may furnish the principal recording material of the future.

The number of times a record can be played depends on how carefully it is handled, but it should stand fifty playings before the quality of its music deteriorates seriously. Two hundred playings is sometimes given as standard, but most records show considerable wear even after ten playings, unless one of the most modern light-weight needle holders is used. Careful measurements are made in the control laboratories on all recording materials, and a record is considered to be worn out when the noise made by the needle during pauses in the music has increased three decibels above its original value.

Thorn and fiber needles are widely used for playing records in the home because they reduce needle-scratch, but they do

this somewhat at the expense of musical quality. A needle of woody material does not transmit high-pitched vibrations along its length so well as does one of stiff metal, and so tends to eliminate scratchy sounds, but at the same time it reduces in intensity the higher overtones of speech or music. Since fiber needles wear away faster than the record material, records which have been played with such needles last longer, and often a good needle of this type will play a dozen or more records without resharpening. Hard needles of tungsten or chromium-plated steel last for many records and give good tone quality, but may wear the record material unduly. The commonly used steel needle gives a compromise between record wear and tone quality, but wears away rapidly itself.

An ideal solution to the needle problem has been reached in a permanent diamond-pointed needle which is fitted to an attachment so light that neither needle nor record are worn appreciably in hundreds of playings. Since such a device is too costly for use in any but the most expensive installations, further research is needed to find a cheap solution to the problem.

¶ 4

WE ARE ACCUSTOMED TO ASSOCIATE SOUNDS of one quality with violins, of a second quality with canaries, and of a third quality with streetcars. Actually these differences in quality arise from differences in the intensities of the various harmonics in the respective sounds, which are reflected in the differing shapes of their respective wavy lines. The sound from one canary differs only in line shape from that of a thousand tuning forks, or the squeak of a barn door on rusty hinges, or any other sound. Now if a piece of sheet-iron or

cardboard could be made to vibrate in such manner as to produce sound waves identical with those from a canary, for example, a canary is what the ear would hear; and to do this the cardboard need only vibrate in accordance with the contours of the appropriate wavy line. If a person could wave his hands rapidly enough a few inches from his ears, he could produce music which would sound exactly like that from a hundred-piece symphony orchestra, though to do so would require that he be able to move his hand irregularly to and fro 15,000 times a second! This is in effect what a loud-speaker is supposed to do. It is merely a piece of cardboard, wiggled by an electromagnet in accordance with the dictates of a varying electrical current which has come from a radio receiver, a telephone, or a phonograph, wherein it has been molded to fit the contours of some sound wave.

A small vibrating diaphragm two or three inches in diameter produces sounds too faint to hear except in an earphone, and the early attempts to strengthen these sounds by sending them through a horn had fundamental limitations, for most horns suffer from the innate egotism called resonance. Since a horn is something of a musical instrument in its own right, when asked to transmit a vibration frequency which happens to coincide with one of its own favorite tones, it will respond over-enthusiastically. A similar result might be expected if a beautiful poem were to be read by an orator who shouted ten times louder than usual whenever he came to the word *I*. The perfect loud-speaker should respond with equal deference to vibrations of all sorts, whether low-pitched or high.

When more faithful loud-speakers were needed for radio receiving sets the problem of developing them was attacked by scientists in the Bell Telephone Laboratories, and by C. W. Rice and E. W. Kellogg of the General Electric Laboratories.

They discarded the horn entirely, and used a larger diaphragm, usually in the form of a flat paper cone, which was found to respond more evenly to the tone spectrum. Many of the first cones showed quirks of their own, such as rattling at the higher frequencies, or failing entirely to produce low tones, but by introducing baffle boards and resorting to various tricks which became obvious when careful measurements of their sound production were made, most of these quirks were eventually removed.

Many fine modern reproducers contain three or more loudspeakers. One large speaker, descriptively called a "woofer," responds to the low tones, and for the high tones two smaller speakers called "tweeters" are used, inclined at a slight angle to each other. This angle is useful because, while low-pitched sounds spread out in all directions, high-pitched sounds tend to radiate from the speaker in a direct beam. A listener who is sitting to one side of the speaker may then hear the low tones louder, in proportion, than the high, unless some means is taken to offset this effect. The effect can be noted in outdoor bandstands in which a curved sounding board is used to throw the sound out into the audience. Those sitting in front of the stand may get a well-balanced sound mass, while to a listener sitting far around on the side may come only the "oompah-oom" of the bass tuba and the thud of the big bass drum. One listener from the sidelines at such a concert reported that he had recognized only one tune, "The Star-Spangled Banner," and his recognition of this was visual.

To study the response of apparatus to sounds of all pitches, from the highest treble to the lowest bass, physicists use instruments which count the number of vibrations striking the ear or the microphone each second. These instruments show that to reproduce all kinds of music perfectly a phonograph

should respond faithfully to vibration rates between 30 and 15,000 per second. Fidelity must extend from the 30 vibrations a second reached by the bass tuba, the bass viol, and the kettle drum, to the 15,000 vibrations a second required for the high harmonics of the snare drum, the violin, and the cymbals. To vibrate a piece of steel back and forth 15,000 times in a second demands much energy. Unless the engineers are ever on the alert an acoustic device will respond half-heartedly or not at all to the very high tones and the very low tones. Such distortion, even when of a degree not sufficient to affect the clarity of speech, interferes subtly with the enjoyment of music, even though it may be difficult for a listener to be sure that something is wrong.

Since all modern radio receivers contain a vacuum-tube amplifier which is especially designed to amplify the electrical wavy line, and a loud-speaker to change this into sound waves, all that is required to produce a modern electrical phonograph with such a set is to add a turn-table with which to spin records, and a needle-holder and pick-up device to transform the mechanical wavy line into electrical form. The phonograph and the radio have thus conveniently gone into a partnership which has resulted in advantage to both.

Even when an undistorted, scratch-free melody comes from a sound reproducer it will not sound entirely natural unless two requirements are fulfilled. First, the record should be played at the same loudness level at which it was recorded, for the human ear has a peculiarity which makes a tone of a given pitch sound lower as it is made louder. If a selection be only one-tenth as loud when reproduced as when originally played, the distortion in the listener's ear may be very marked. Good recordings can seldom be played at the proper

volume without disturbing the neighbors, but if this can be done it usually results in greatly improved quality.

The second requirement is that two sound channels be provided, so that the two ears will hear slightly different sounds, as they would have in the room in which the sound was originally produced.

This point is well illustrated by Oscar, a tailor's wax dummy with microphone ears which is held in much affection in the Bell Laboratories. If a listener holds to his right ear a receiver which is connected to Oscar's right microphone, and to his left ear another receiver which goes to Oscar's left microphone, then closes his eyes and listens, he feels that his head is actually inside Oscar's, whether they be separated by ten feet or a thousand miles. For all practical purposes Oscar's microphones are the listener's ears, and whatever happens near them sounds as though it were happening near the listener. It is strikingly true that not only is two-ear hearing necessary to give one an idea of where a sound originates, but it is also absolutely essential if the sound is to have accurate quality and naturalness. Take one receiver from an ear, and Oscar's weird power vanishes. To accomplish such a result with a phonograph would require two synchronized sound tracks or records and two speakers, which at present seems too complicated to be desirable. But the possibilities of such three-dimensional or stereophonic recording should not be overlooked.

5

MANY INVENTORS WORKED OUT METHODS of making motion pictures talk and sing before the electrical methods needed to make this really practicable were available. Eugene Lauste is

known as "the father of the sound film" for he was working on a photographic system of recording sound as early as 1900, and by 1906 had obtained patents on many basic methods which are still used. Edison had hitched his crude phonograph to a cinematograph in 1894, but the public preferred them apart. In 1910 he tried it again, but his talking movies ran for only four months in vaudeville and then departed. A satisfactory voice for the movies did not require an invention—it waited on the development of many new materials and new technics, but principally on the development of vacuum tubes.

Most of the elements needed for satisfactory sound recording were available in 1920, but it was not until five years later, when the facilities of several great industrial research laboratories were applied to the problem, that sound reproduction became good enough to be accepted by the public as a voice for motion pictures. Suddenly in 1927 the sound pictures were found satisfying, and the motion picture industry was revolutionized overnight. The use of preserved sound has increased continuously since then, and now a single firm of distributors may handle thousands of miles of wavy lines in a month.

At first the disk storage methods of the ordinary phonograph served, with some modification, for the voice of the screen. Disk records became larger and were packed fuller of sound so that they would play for eleven minutes instead of only four, and the sound track was started at the inside of the record instead of at the outside, so that the shorter wiggles near the center would be traversed while the needle was still sharp. Disks are still sometimes used to carry screen voices, but they are less convenient than the newer method in which the wavy line is stored photographically on the film. Records

are likely to become separated from the films to which they belong, while an optical record, stored directly on the film with the picture itself, cannot be misplaced.

A strip only an eighth of an inch wide along the edge of a motion picture film is sufficient to carry an optical sound record. The variations in blackening of this record, which in one system of recording look like the teeth of a stubby comb, and in another like narrow black ripples, cut at a speed of ninety feet a minute across a light beam which shines on a photo-electric vacuum tube. This tube converts the pulsations of the light beam into fluctuations of an electric current, which when amplified actuate the loud-speaker and produce the sound waves.

Those ripples on the record which are to produce tones of the highest pitch are only a hair's breadth apart, and are therefore difficult to keep cleanly separated and unblurred. Their images were finally clarified by using ultra-violet light instead of ordinary visible light to record the sound track on the film. The short ultra-violet waves, for which methods of control had previously been developed by research workers in fundamental physics, gave much sharper images than did visible light, and when they were used the voice of the screen immediately improved. Handling the ultra-violet light required special photographic equipment, but this also was fortunately at hand, as similar problems had previously arisen in researches on the structures of atoms.

When music is taken from film there is no needle to wear the record, for its place is taken by the thin beam of light, narrow as a needle is sharp, which scans the optical waves as they rush past. Unfortunately the long flexible ribbon of photographic film must be coiled and uncoiled twice whenever it is used, and this tends to break and tear it. To protect

the film from scratches and grease smears is difficult also. Eliminating the needle might be expected to eliminate needle-scratch, but every accidental variation in opacity of the film is translated into undesired sound, whether arising from the irregular distribution of the silver grains which form the image, to scratches, or to stains produced by chemicals which have not been properly washed from the film. As a film wears out it begins to sound worn before it begins to look worn, for to the eye scratches are submerged in the general picture, while to the ear each scratch sticks out as a pointed pin of sound.

Will records stored on film, requiring no needle for playing, ever supplant disk records for home phonograph use? A hundred narrow ultra-violet-recorded sound tracks could be put side by side on a single film, and thus twenty hours of playing time—all the symphonies of a great composer—could be stored in a single standard film a thousand feet long. Or a whole library of popular songs could be carried by one long-playing record. But films are much more fragile than disks and are less convenient to handle, while the difficulty of turning at will to any part of such a musical library would limit its advantages, and the necessity of providing separate selections to suit individual tastes must also be considered. Musical libraries on film may have special uses, however, and we must not overlook the possibility of arranging to turn to any desired section of a film by pressing buttons on a keyboard. Instead of being owned and kept at home, such wholesale records might be kept in central studios from which they could automatically be played, music from them being transmitted over special telephone lines. A subscriber who felt in the mood for the Sextette from *Lucia* need then only dial

DOnizetti 621 on his special line to have this selection piped electrically to his high-fidelity reproducer.

¶ 6

ONE OFTEN HEARS PSEUDO-SCIENTIFIC STORIES about remarkable devices supposed to have been purchased from their inventors and then buried by powerful interests, who feared the loss of rich incomes from their own inferior equipment if the world were allowed to profit by the new inventions. Tales of this sort are frequently recurrent. A phenomenal magnetic phonograph, said to require no needles and to give perfect reproduction with records which do not deteriorate with use, is the subject of one such story. A well-known writer has publicly implied that this invention should have made obsolete all present phonographs and dictating machines, and infers that by neglecting it American scientific initiative has betrayed the public interest. Has the "phonograph trust" suppressed a perfect phonograph for fear it would stop the profitable sale of disk records?

As with most such stories, plausibility is lent by a grain of truth on which entirely erroneous conclusions have been based. The remarkable magnetic phonograph turns out to be nothing but the telegraphone, which we have met before as the self-answering telephone. Storing a sound pattern in the form of magnetic wiggles in a long steel wire has been perfectly feasible since Professor V. Poulsen of Copenhagen first suggested and tried it in 1903. No needle is required, for the magnetic forces stored in the wire induce in a coil electric currents which reproduce the stored sound. The record can be erased by simply drawing the wire past a powerful magnet,

when the steel will be ready to be filled again with recorded sound.

Here the advantages of magnetic recording end and limitations to its usefulness begin to appear. Though such a record is permanent—and a wire has been made to disgorge a load of understandable speech even after carrying it for thirty years—it must be kept away from thunderstorms or electric motors which produce stray magnetic fields. Research through the years has improved the quality of its reproduction, but this is still not superior to that of mechanical or optical recording when the length of wire in a record is kept within reason, for, as with the other methods, the short waves which store the high-pitched components of sound tend to blur together if packed too closely. Again, a wire or ribbon hundreds of feet long is less convenient to handle than a simple disk record which keeps its sound track carefully coiled up in a neat spiral. But problems of copying set the most important limitation to magnetic recording. When we realize that nearly two million copies of a record may be sold, as in the case of such songs as *Ramona*, *Blue Heaven* and *Prisoner's Song*, the importance of simple methods of duplication, similar to printing, is obvious. Magnetic records can be copied only by playing them through and recording on other wires, each running through an individual recording machine. Such limitations prevent this type of recording from being considered seriously for the phonograph field.

That the same piece of steel wire can be used thousands of times for magnetic recording, and hence would be the cheapest known type of "temporary record" material, suggests its usefulness for office dictation. But here again a coil of wire is less convenient than a cylinder for carrying dictation to a typist. Magnetic recording comes into its own only where a

permanent installation can be made, and in radio broadcasting studios and in newspaper offices it is finding increasing use.

Picture the busy news editor with three telephones ringing at once. Fitted with the magnetic-recording attachment, his telephone instrument becomes truly a receiver, for he need only shout "Go ahead" into the phone, flick the recorder motor into action, and without further responsibility at the moment leave the recorder to absorb the message.

If a popular comedian wishes to amuse his listeners throughout a nation, he need no longer concern himself with repetitions necessitated by differences in time, for the magnetic reproducer (like several other recording methods) has been developed to such perfection that when used for radio broadcasting the listener cannot tell whether he is hearing an original presentation or a recording. During the first broadcast the steel wire, gliding silently past its pick-up, listens to what goes out over the ether and stores this carefully in its magnetic interior; then, an hour or a day later, it will repeat every word to the last minor inflection. Many of the short-wave programs in Great Britain now consist largely of magnetic transcriptions of previous regular broadcasts. The magnetic phonograph usefully supplements the mechanical and optical phonographs, but it can never be expected to supplant them.

New types of sound track will doubtless be found practicable as research makes new tools available. Reproduction of a sound track by printing on a paper tape has been carried out successfully in Europe. A phototube picks up the fluctuating light reflected from the tape and sends out a pulsating electric current in synchronism with the black waves inked on the

white paper passing before it. If the sound track could be compressed to smaller size, the printing method might conceivably be used for producing optical disk records. An ideal solution of the phonograph problem would result, for no needle would be required, records would not wear on playing, and duplication on printing presses should be so inexpensive that if we should want a daily morning record tomorrow it would cost no more than the *Morning Daily Record* of today.

The storing and re-creation of sound is a scientific miracle, perfected by the research physicist when he learned to induce co-operation between inanimate dancing atoms and electrons. If science seems to be making the production of music more mechanical, it is with the purpose of making music itself less mechanical and more natural. If musical apparatus seems to be getting more complicated, it is in order that production of music can be made simpler. If scientists are taking more trouble with sound production, it is in order that listeners and performers can give less attention to irrelevant features of the musical art and more attention to its important features. From all this is arising a new development of music which should delight the ears of the world.

XIV

OUTWITTING THE WEATHER

The sun shall not smite thee by day, nor the moon by night.

Psalms

MARK TWAIN made his oft-quoted remark about the weather just in time, for though people talk about weather as much as ever, scientists now have really begun to do something about it. Not much has been done in the way of changing the vagaries of a nor'easter, or increasing rainfall in the Mojave Desert, of course; but man can control the weather in his immediate neighborhood at least during the nine-tenths of his existence when he is indoors.

The first operation in changing weather is to find out what kind will need changing. Predicting the weather is a field of human interest for which physics must take full responsibility. Whether it rains or shines or snows depends on the physics of the atmosphere; and the meteorologists who dedicate themselves to following and predicting the changes in this fertile topic of conversation are applied physicists of a most determined and interesting sort. Weather predicting a day in advance is gradually getting to be on a fairly sound basis, though with more emphasis on the "fairly" than one would like. Predictions made a week in advance are on a more shaky foundation. Predictions made a year in advance, covering long-term periods of drouth and dampness, are still rather in the hopeful stage, though some meteorologists believe

that great possibilities are appearing as more data are recorded.

Intensive research is going on in the science of meteorology, and it is quite reasonable to expect that, before many more years have elapsed, far more precise and accurate short-range forecasting will be possible. One new development which shows great promise is the polar-front theory, lately incorporated by the United States Weather Bureau into its official methods of prognostication. This theory deals with the results to be expected when a great mass of cold air from the North Pole meets a mass of warm air from the tropics. It is proving to be a powerful new tool in weather predicting, and was first formulated by one of a famous Norwegian family of weather physicists, Professor J. Bjerknes; Norwegians seem to excel in the study of weather, perhaps because they live where so much of it originates.

In the midst of a host of pseudo-scientific methods of long-range forecasting, which inevitably arise in connection with so important a subject as the weather, there are a few attemped methods which are being based on real research. Dr. Charles G. Abbot of the Smithsonian Institution has for years been measuring the amount of heat received from the sun by the earth. Smithsonian stations in three of the most arid regions of the globe are recording the sun's radiation daily. In almost treeless and waterless wastes, high up on mountain peaks, conscientious observers in Chile, in South Africa, and in western America have been taking records for many years. Although the heat received from the sun rises and falls only about one per cent, Abbot claims to find correlations between changes in solar radiation and temperatures at widely separated stations over the earth. By going back through his records, and by studying the records of earthly

weather as recorded in the growth rings of trees, which have been followed back for over two thousand years, together with other phenomena, Abbot points out what appear to be recurrent cycles in the weather which, if real, may be of great value in predicting long-range trends in the succession of fat and lean years. If such long-range predictions turn out in the end to be as easy to make as detailed predictions for two weeks in advance, they will be of fundamental importance.

Our knowledge of weather can be improved most rapidly by providing better means of collecting data. Airplane observations on physical conditions in the upper air are being carried out daily from a number of stations, but each flight costs about $25, and the airplane does not rise more than a few miles. A cheaper and more comprehensive survey can be made by sending up sounding balloons carrying small radio transmitters weighing only a few ounces, which flash back signals telling all about the temperature, air pressure, and humidity in the various reaches of the atmosphere as they ascend mile after mile. Even small photo-cells are sometimes carried; and these dictate radio messages telling how bright the light is inside clouds through which the balloon is passing —true silver-lining detectors. Sitting on the ground, watching his automatically recording radio receiver, the weather man can measure the exact thickness of each cloud as his balloon rises through it. When the balloon is not in a cloud he can follow it with a telescope to measure the drift of the wind.

Some sounding balloons used for observing atmospheric conditions up to twelve miles above the ground are fifteen feet in diameter when they start to rise, and if of rubber, they swell as they rise higher and higher, and eventually burst. Sometimes two such balloons are tied together. Their combined buoyancy is sufficient to lift the radio and mete-

orological instruments, and when one balloon bursts the other falls slowly to the ground and returns the instruments unharmed. Occasionally a balloon is lost with all its instruments, but modern methods are cutting down the cost of such apparatus, and the information sent back before it plunges to loss or destruction makes the venture worth while.

Once we learn what weather is in store, what can we do to modify it? Accurate prediction of frosts twenty-four hours in advance, a particularly ticklish job, is worth millions of dollars to growers of citrus fruits. Smudge pots have been in use for orchard protection for many years. They aid somewhat by heating the atmosphere (most ineffectively), but more by creating a pall of smoke which cuts down loss of heat from the ground by radiation to a clear sky. On the other hand, how amused the early settlers would be to see modern newspaper photographs of a Georgia peach grower burying cakes of ice under his trees to forestall early blooming in a warm winter!

As to producing rain from the sky artificially in dry weather, Dr. W. J. Humphreys put the matter succinctly when he said that there are two kinds of rain-making schemes —those that won't work, and those that are too expensive to use. The process of bombarding clouds with dry ice comes in the latter category. The atmosphere is simply too big for human control.

Long ago man learned that the best way to control climate was to build himself a house and concentrate on improving the weather inside this. To help with such control, science and technology have much to offer; and now air conditioning is being applied not only in places of business and amusement, but in railways, homes, and even in automobiles.

2

WE ARE LIKELY TO THINK OF BREATHING as an incidental nuisance of life, which, if its absence were not so painful, might well be dispensed with. Yet almost two-thirds of our bodily energy comes from the free air we breathe; three pounds of food and four pounds of water a day will keep the body functioning, but these would be of little use without 34 pounds of air daily. Since, on the average, we spend 87 per cent of our time indoors, much can be accomplished to improve health by insuring that the 30 pounds a day of indoor air we breathe is delivered in good condition. This air should be clean, of the proper temperature and moistness, and above all, slowly moving. Motionless air, no matter how pure, is stale air.

To put air into good condition for breathing requires at least five operations—it must be heated or cooled, moistened or dried, cleaned, deodorized, and circulated. These are all physical operations involving energy; and though air conditioning has for some time been in the hands of the engineer, tricks of the physicist and physical chemist are what have made possible its present efficiency. More such tricks appear to be needed to carry its development further.

What temperature and humidity should air be given to be most healthful? If the breather of air is to go outdoors at all, the answer must depend upon outdoor conditions. Careful tests have shown that in winter children kept in schoolrooms held at 68° F have fewer colds than those kept in hotter or colder rooms. In summer, indoor temperatures must be kept relatively high to avoid sudden chilling on entering the house;

if the outdoor air is as hot as 95° F, the indoor air should not be cooler than 80° F.

The relative humidity of the air—its actual moisture content relative to its maximum possible moisture content at a given temperature—should be adjusted to be between 30 and 70 per cent, summer and winter. Winter air is dry, its relative humidity falling at times below 20 per cent in heated buildings. In summer, on the other hand, the humidity may rise far above 70 per cent. The high moisture content of the air in summer prevents proper functioning of the body's own cooling system—evaporation of perspiration—and thus gives rise to that lassitude which inspires the familiar comment, "It isn't the heat, it's the humidity."

In winter it may be desirable to add a gallon of water an hour to the air of a large room, while in summer the removal of a gallon an hour may be necessary to achieve comfort. In motion picture theaters an audience of 1000 persons can be expected to add 12 gallons of water each hour to the moisture content of the air, unless the picture is very exciting, in which case the theater air-conditioning plant must be prepared to remove 18 gallons an hour.

Air can be cooled, cleaned, and brought to the proper humidity by a single operation. Strangely enough, air can be either dried or moistened by spraying water into it. When air is cooled, as by expanding, it will give up a portion of its moisture to any cooler surface, and a cool surface of water serves as well as any other. Thus a spray sufficiently colder than the air can be used to remove water from the air, while a warmer spray can be used to add moisture to it. By means of a furnace-refrigerator combination the water can be brought to such a temperature that when sprayed into the circulated air it will adjust both temperature and humidity

to the proper values, and at the same time wash from the air all dust and odors.

Despite the term "winter air conditioning" which builders have introduced to describe modern installations of a furnace and a humidifier, no building is really air conditioned unless provision is made to cool as well as heat its air. It has always been easier to warm a room in winter than to cool it in summer, and cooling still costs from two to three times as much as heating. Many fuels are known which give off heat energy when burned with the oxygen of the air, but few cheap materials are known which might be called anti-fuels—that is, which grow cold when mixed with air or water. Some chemical reactions absorb heat and hence generate cold, to be sure; but these are far too expensive for refrigeration purposes. Physical methods are best for producing cold.

Ice costs at least $4 a ton; yet 2000 pounds of ice in melting will absorb only as much heat as can be generated by burning 20 pounds of coal. A typical home in the tropics would need about two tons of ice a day to cool and dry its air properly in summer, and the home owner who relied on ice for cooling might run up an ice bill of $240 a month! Fortunately, though, since electric or gas refrigerators can produce cold at about one-third the cost of melting ice, cooling a small house in the latitude of New York need cost no more than $240 a season. Even so, air conditioning is still rather expensive for ordinary home use, and is economically feasible only for places where many persons congregate, such as theaters, stores, and trains. It has been found, however, that if restful sleep is obtained at night, the human organism can stand more humidity by day without fatigue; and small conditioners designed to be placed in partially opened windows can cool the air in a single room very economically.

Installations of this sort in bedrooms do much to make living more comfortable in regions of high humidity.

When is air fresh? Ordinarily one would say, When it contains plenty of oxygen and little carbon dioxide. This is the case when the air has been breathed from the leaves of a plant more recently than from the lungs of a human being. Carbon dioxide is seldom present in dangerous amounts in even the closest room, however, and the stuffiest closet usually contains plenty of oxygen. Air which is moving, free from objectionable odors, and dry enough to absorb considerable moisture is what most persons call fresh.

Odors can be removed from air not only by washing it with sprays of water, but also by drawing it through a filter containing finely divided charcoal, or by passing it through an ozone generator. Ozone is a very active form of oxygen which can be produced by pulling air through a gap between metal plates across which a high-voltage electrical discharge is jumping. Oxygen molecules in the air are thus torn apart electrically, and groups of three atoms from these torn molecules may cling together temporarily as an ozone molecule. When such a molecule bumps into a molecule which carries, let us say, the smell of cooked cabbage, two of its atoms may revert to the ordinary oxygen manner of existence, leaving the third atom bereft of companions. Supposedly it turns to the cabbage molecule and, fastening itself to this, converts it to a new molecule of different or no smell, but there has been much argument as to whether ozone really destroys odors, or merely masks them with a stronger odor of its own.

Ozone is of no known benefit to health; in high concentrations it is poisonous. Most ozone generators produce small quantities of other poisonous vapors, and all of these together may cause headaches if purposely inhaled, but are harmless

in the small amounts used to eliminate kitchen odors. Many air-conditioning experts believe, however, that ozone has no place in the kitchen, though in cold-storage plants it may be of value to reduce the formation of mold.

In some large cities hundreds of tons of dust are deposited each year on every square mile of ground—eighty pounds to a dwelling. Soot, dust, germs, and pollen introduced into homes can be removed in air conditioners by pulling the air over glass wool coated with grease, or by washing the air with water sprays. Or the air can be passed between two highly electrified wires which charge the dust particles, these being then drawn from the air stream and caught by charged wire grids. Heavy clouds of smoke can be blown through such a dust catcher when it is not in operation, but as soon as its power is turned on no smoke comes through, no matter how densely it may continue to stream in.

Air which is being conditioned must be pumped through ducts, and to do this requires much energy. Even so modern an air-pump as the electric fan has recently been found susceptible to streamlining, with great improvement in its efficiency. Calculating the most efficient shape for a fan blade is a very laborious job of mathematical physics, but a wooden model of the projected fan can be whittled out and made to reveal visibly its own failings. Paint sprayed into the air which is sucked in by the whirling model will be deposited most thickly on those parts of the blades which are pushing most air into motion. The wooden blades can then be changed by whittling away one lazy spot after another until they are found to become uniformly coated all over with paint. Fans formed to shapes arrived at in this way have been made to pump twice as much air as their predecessors, though requiring only an equal amount of power to keep them turning.

More than $85,000,000 worth of air-conditioning equipment was installed in America in a recent year. In one automobile foundry a new air-conditioning plant removed 42 tons of dirt from the air during the first week. A railroad system reported that air conditioning of cars increased summer travel over its lines by one-fourth. Candy factories, textile mills, paper-manufacturing plants, all have found the installation of air-conditioning apparatus economical because of savings through the elimination of "off" days, when humidity conditions affect adversely both personnel and product.

Some industries have found the installation of air-conditioning equipment imperative. The deepest gold mines of Africa were formerly so stifling at times that not even the hardened Kaffir natives could work in them. Humidity sometimes rose to 100 per cent, putting the body's cooling system entirely out of operation, since perspiration could not evaporate at all; and when temperatures rose to 100° F every worker acquired an artificial fever. Then the mines installed refrigerating plants, one of which could create each day a mountain of ice weighing four million pounds. But instead of making ice, the refrigerators were set to cooling 150,000 cubic feet of air a minute, which was pumped down into the mine to make working conditions tolerable, as far as air was concerned.

Several New York skyscrapers are now air conditioned. Probably in the distant future air conditioning will be supplied to whole communities instead of in individual homes, with cooling brine pumped beneath the streets from house to house. One large installation can be operated much more efficiently than a thousand small ones. When such city-cooling projects have been installed, and homes are air condi-

tioned as a matter of course, June days should not be so rare as now—at least indoors!

¶ 3

ONE OF THE QUICKEST WAYS TO PRODUCE COLD is to let a liquid evaporate rapidly; if water, for example, is boiled in a high vacuum it will freeze solid almost instantly. Another easy way to produce cold is to compress a vapor, thus heating it, then cool it with running water or flowing air, and allow it to expand. It will then become much colder than its surroundings. By repeating this process over and over, always carrying heat away while the vapor is compressed and letting little come back when it is expanded, heat can be pumped indefinitely out of a refrigerator box into the air of a room.

Such methods can be used with any vapor, but most convenient for use in household refrigerators is a vapor which becomes liquid at ordinary temperature without being highly compressed. Ether, ammonia, carbon dioxide, sulphur dioxide, and fluorine all have been found useful in refrigerators, but some of these are poisonous, others explosive. Though the number of suitable vapors is limited, fortunately chemists can invent new ones by merely rearranging atoms to form new varieties of molecules. Such a material now widely used in refrigerators, called "Freon" for short, has molecules which are closely related to those of carbon tetrachloride, used as a fire-extinguisher fluid. Freon is an almost ideal refrigerating vapor, for it is neither poisonous nor explosive, will not burn, has little odor, does not corrode metals, and condenses to liquid form on application of moderate pressure.

To heat any piece of matter requires energy, but to cool it also requires energy. From these two laws of physics it follows

that both stoves and refrigerators must be fed fuel or power. A stove builds a thermal hill whose temperature is higher than that of its surroundings; a refrigerator digs a thermal hole whose temperature is lower. Just as the dirt removed from a hole dug in the ground can be piled into a hill, so the energy which a refrigerator carries away from a spot which it is cooling can be piled into a stove to heat it.

The center of attention in kitchens of the future may well be a large white cabinet, with pots and kettles simmering cleanly on top, while in lower compartments ice cubes slowly freeze and food is kept cool. Between the two sections (stove and refrigerator), kept carefully insulated so that heat cannot leak from one to the other, will be a heat pump, diligently pumping energy out of the cold section into the hot section.

The usual kitchen stove utilizes less than one-fifth of the heat in its fuel, four-fifths going up the chimney or heating the kitchen. The heat energy which is wasted by most kitchen stoves is more than enough to operate the common household refrigerator. The heat pumped out of a present-day refrigerator is usually insufficient to operate a stove, but devices are on the market by which it can be used for providing domestic hot water.

Nearly two million refrigerators are now manufactured each year. Most are of the mechanical type, in which vapor is compressed by a pump and allowed to expand in the walls of a cooling chamber in which ice cubes or food can be frozen. The entire compressor unit can be sealed tight with its oil and vapor inside, and left running as continuously as needed, at a cost for energy of a few cents a day. No one yet knows what the average life of such a refrigerator unit is, for some have been merrily pumping heat out of an insulated box into the air for ten years without overhaul or oiling.

Electronic vacuum tubes enter intimately into the construction of modern refrigerators. Steel tubing is used to form the intestinal tract which circulates the refrigerant, and this can be made cheaply by stamping into two flat steel plates, under 1300 tons' pressure, depressions representing the right and left halves of the zigzag tube. These can then be welded together electrically in less than three minutes. The welding operation is much like the operation of an electric sewing machine—the two half-sections of tubing are literally sewed together with electricity. At each "stitch" a pulse of current flows from a copper rod down through the upper plate into the lower, welding them together. If too much current flows in the 1/120 of a second allowed for a stitch, the metal will be burned; if too little, the plates will not stick together. Adjustment of the pulse of current is entrusted to thyratron tubes, which spit sparks of exactly the proper strength into each stitch. All the operator need do is follow the convolutions of the pipe on the upper plate as he sews the two plates together.

Each welded pair of plates, before it is used in a refrigerator, is tested for leaks by filling it with air compressed to 100 pounds per square inch, immersing it in warm water, and watching it for bubbles. If air-tight, it is fastened to the compressor which is to serve it, is evacuated with high-speed pumps, and is then charged with sulphur dioxide or freon. Finally it is mounted in an insulated cabinet, and a new community of atoms is set to work digging thermal holes to keep food fresh and wholesome.

If a current of electricity is sent through a carbon rod, the rod becomes hot. A very desirable discovery would be a rod of something which would become cold when electricity was sent through it. Phenomena whereby cold can be generated

by the flow of electricity are known, but all are too inefficient or costly to be practical. However, two students at the Royal Institute of Technology in Stockholm, Carl Munters and Baltzar von Platen, worked out a remarkable system of refrigeration which, while somewhat more complicated than the simple mechanical compressor, has no mechanical moving parts and hence capitalizes on the fact that molecules cannot wear out. This system is now marketed under the trade name of "Electrolux."

Such refrigerators can be operated on gas, electricity, or any fuel, in fact, which will generate heat. The heat energy keeps three fluids in circulation inside the refrigerating system: ammonia vapor, water, and hydrogen gas. The hydrogen is used to keep the water circulating, and the water the ammonia. As a result of these circulations, the ammonia is continuously evaporated inside the cooling unit where it absorbs heat. When the thermostat on such a refrigerator signals that it should get colder, more heat is turned on. Turning heat into channels which force it to dig its own cold spot is indeed a triumph of mind over energy; in some future day the sunlight falling on the roof of a house may quite conceivably be used to operate refrigerators which keep the house cool.

The only limit to the depth of the thermal hole which a properly designed refrigerator can dig in its own insides is set by the absolute zero of cold at which all molecular motion stops (−459.69° F). Recently temperatures have been reached which are not more than a few thousandths of a degree above this nadir of cold. Physicists would like to have vast refrigerators in which they could experiment on matter in bulk kept at these low temperatures, for many well-known phenomena are greatly altered under such frigid conditions. Some metals lose their electrical resistance entirely at tem-

peratures a few degrees above the absolute zero, and currents of electricity can continue flowing through such frozen wires for days after all voltage-producing sources have been disconnected from the circuit. If electrical power lines could be kept at a few hundred degrees below zero F, high voltages would be unnecessary, for currents of hundreds of amperes might then flow unhindered for thousands of miles.

When rubber is immersed in liquid air it becomes as brittle as macaroni, and can be ground to powder in a meat grinder. The lightest oil becomes a solid crystalline mass. At the temperature of liquid hydrogen even air becomes solid, and what solid air can do for industry can only be surmised. Its much warmer relative, solid carbon dioxide, is already finding wide use as "dry ice."

4

BEFORE A HOME IS AIR CONDITIONED its walls should be made poorer conductors of heat and its windows sealed tighter than is customary in most frame houses at present. In a wooden house the air at the ceiling of a room may be 25° F warmer than at the floor level. One eccentric old German physics professor gave up hovering about his porcelain stove in winter; he piled tables one upon the other, climbed atop the pile, and wrote his books perched as close to the ceiling as he could get. If the outer walls of his dwelling had been made of some material which retarded the passage of heat, he could have come down to the floor again, for heavy cold air chilled by the walls would not have collected there.

Glass bricks let heat through but slowly; the comparative coolness in summer and warmth in winter of stone or brick buildings has long been noted. Wooden houses can now be

made equally comfortable by lining their roofs with blankets of mineral fluff, and by boring small holes in their walls in out-of-the-way places and pumping the spaces between inner and outer walls full of woolly material made from rock or glass which has been melted and blown into fibers. Such inorganic materials, for which insects and rodents have no use, hold air trapped between their fibers. Air is a fine insulator of heat if it can be prevented from flowing, and this the glass or mineral wool does to perfection.

A modern substitute for mineral wool is aluminum rolled into extremely thin sheets of foil, and crumpled. The shiny aluminum reflects heat rays which try to enter or leave the house through the walls, and thus serves the same purpose as the mirror surface of a vacuum bottle. In sheets less than a thousandth of an inch thick the aluminum foil cannot conduct much heat through its substance, and air is trapped in its crumpled folds and is thus prevented from flowing. Aluminum-foil heat insulation is widely used in battleships, in airplanes, and in refrigerator cars, where lightness is important.

When a house is properly insulated, fuel bills can sometimes be cut almost in half. Air conditioning then becomes inexpensive so far as upkeep is concerned, though still somewhat costly for installation. Insulated houses last longer than ordinary frame houses, for they are not subject to such violent internal strains from stretching as their walls swell and dry out and become alternately hot and cold.

If a large heat-insulated storage reservoir for water were available for every house, homes could be heated in winter and cooled in summer very cheaply. In the summer the water could be sent through glass-covered trays which would absorb the infra-red rays which otherwise would heat the house un-

duly; and as the water was warmed it would pass into the reservoir and be replaced by cooler water. By late fall the water in the reservoir would be quite hot, and it would then serve to keep the house warm in winter. This method has actually been tried; but, because of its high cost of installation, it is hardly practicable at present.

Modern buildings are being conditioned not only for heat but for noise. The story of bagasse, the waste fiber of sugar cane, shows how science can solve a building problem and at the same time provide use for a product previously wasted. When the stalks of cane have been crushed between heavy rollers and all their juice has been extracted, a coarse fiber remains which is too tough to feed to livestock, and will not even decay if plowed back into the soil. One mill produced 300 tons of this bagasse a day, and at some inconvenience burned it as part of the fuel with which the furnaces were stoked. Now the material is compressed into an insulating board and made into special panels for sound treatment of rooms. Perched in the ceiling of an auditorium, the hole-filled tiles of coarse fiber lie in wait for approaching sound waves and, when these strike the holes, swallow them. Annoying echoes which would add to the noisiness of a room are thus eliminated.

For the sound, light, and heat conditioning of buildings, physicists have provided many new measuring devices which help in checking on the efficiency of the methods used. To the mechanical side of the building industry also the physicist has something additional to offer in his new types of strain gauge. Inside such great structures as Boulder Dam strain gauges have been placed which will tell electrically at any future time just what pressure exists within the concrete mass.

If such gauges were inserted in bridges and skyscrapers, an engineer could connect an instrument to the wires going to any gauge and figuratively ask the question, "How's the tension up there?" If the molecules in the gauge gave the answer "All's well," there would be no need for worry, come earthquake or hurricane; if they answered, "The strain is getting pretty great," support could be provided at once.

Earthquakes are a constant menace in many parts of the world. With tools furnished by physicists, engineers have learned how to compute possible stresses and to construct buildings which will yield somewhat to the earth's vibrations, but not too much. Small models can be built to test out the reactions of a given type of building construction; and artificial "canned" earthquakes fed through electronic vacuum tubes shake them exactly as a real earthquake would have shaken their life-sized originals, for the vibrations of many important earthquakes have been recorded, and can be reproduced artificially as that lesser form of vibration, sound, is reproduced by a phonograph record.

Even so stereotyped a job as pile driving is using the new physics. Concrete piles are useful, but if not coated with iron piping they are likely to split or shear if hit too hard a blow. Quartz crystals, of the same type that are used to stabilize the wavelengths emitted by radio stations, are inserted in typical piles, wires are connected to them, and the voltage generated at their surfaces by the force of impact of the pile driver on the pile is measured on the screen of a cathode-ray oscillograph. The physicist watching the screen of this vacuum tube can then tell the pile-driver operator just how hard it is safe to hit the pile as it passes through various strata. Much time can thus be saved, for the pile can be pounded with

blows only slightly less severe than those which would fracture it, yet stronger than those which would be safe if struck blindly.

5

Apart from its traditional use for modesty and ornamentation, clothing serves a fundamental purpose of supplying an intimate air-conditioning plant for the body. A person could be clothed completely by painting his naked skin from head to heels with a colored cellulose acetate in liquid form, spread on like nail polish with a brush; but he would soon suffer a most uncomfortable death when the cellulose material hardened and choked his pores. Instead, this same or a similar cellulosic material is forced through tiny holes in a metal plate, from which it emerges solidified into filaments of rayon; these are twisted together into threads or yarns, the yarns are woven into cloth, and the cloth is cut and stitched into garments of traditional sort. The same molecules of cellulose are applied in both cases, but how different is the physical result!

Cloth should let fresh air into contact with the skin and let out moisture-laden air, while at the same time preventing marked flow of heat either in or out. It fulfills these functions as well as it does only because the human race has accumulated through the ages a surprisingly competent store of textile physics.

The cut of a piece of cloth depends upon how it is woven, its weave on the character of the yarns available, the yarns on the fibers which the spinner used; but most important of all, the fibers depend on the molecules of which they are composed.

Cloth made with wool fibers holds its shape well and resists creasing because the molecules of keratin in wool are actually tiny resilient molecular networks formed of grids of atoms held together by electric and magnetic forces. These grids of atoms behave like tiny bed springs, and provide an extremely resilient fiber, yarn, and fabric. Information regarding molecular structure has recently been used to show how best to attack the problem of pre-shrinking woolen cloth so that suits caught in a rainstorm will not gather themselves into knots.

Under the microscope, wool fibers are seen to be covered with scales and crimped into waves along their length. These two peculiarities of structure make possible the production of felt, for the fibers become easily entangled and can be compressed into a solid mass which holds together well. The scales and crinkles of wool also cause it to appear dull—until when, as on shiny trouser seats, the surface nap has been worn away.

A cotton fiber is found to be a single cell, looking much like a small replica of a 600-foot length of twisted and collapsed fire hose, though only about one inch in length and in proportion somewhat thicker-walled than the hose. The strength of a cotton fiber may be almost as great as that of a steel wire of similar size, but the strength of cotton yarn depends not so much on the strengths of the individual fibers as on the tenacity with which they hold to each other when twisted together in the spinning process.

Silk is valued greatly as a textile material because its filaments are fine, strong, and very long. The silkworm eats the leaves of the mulberry tree and puts the cellulose from these through its own chemical processes, producing a thick, viscous fluid. This fluid is extruded through a pair of spinnerets

to form twin filaments held together with silk glue (sericin), which sometimes reach the amazing length of two-thirds of a mile. The silk yarn of commerce is the sheerest and strongest of the natural fiber strands. Now, however, any one of a number of viscous materials can be made artificially into fine filaments or fibers, and several hundred filaments can be produced simultaneously, each as long as may be desired. Rayon is such a fiber; it is made from the same material that goes into some kinds of motion picture films and phonograph records.

One of the principal physical difficulties encountered in making rayon was to produce holes sufficiently small to form filaments of the desired fineness. Filaments of 0.0004 inch diameter are easy to make, and a pound of rayon of this size would stretch from New York to Moscow. But this is not enough—to fill the demands for ladies' sheer stockings a pound of rayon should be capable of stretching half around the world. An improved material has been made which can be extruded in even tougher, finer filaments than silk. This material, now familiar as "Nylon," bids fair to beat the silkworm at his own job. It is, of course, only a matter of time until silk manufacture by worms will be as out of date as oil manufacture by whales.

Almost every one of the fibers used for textiles has one or more advantages over all others. Perhaps some day science will evolve the perfect fiber having the strength of glass, the fineness of silk, the resilience of wool, the permanence of asbestos, the toughness of cotton, and the right length of filament for optimum spinning. In the search for such a fiber the X-ray spectrograph is indispensable.

When fibers are spun into yarns, great care must be taken if a smooth, uniform, strong thread is to be obtained. If

twisted too tight in one spot, the yarn will not absorb dye properly there, and streaked cloth may result. Handling threads by machine requires dextrous and delicate equipment which operates at speeds so great that the eye cannot follow individual motions. The stroboscope then becomes invaluable. Is this thread being broken by a bobbin which is traveling too rapidly? Or is that gadget—a veritable snake's tongue darting toward one pair of yarns after another—a thousandth of a second slow in reaching out? The flashing stroboscope makes the bobbin or the knotting head appear to stand still, or, if desired, slowly carry out each cycle of its operation.

Cloth which can be sold for ten cents a yard, or even ten times as much, must be woven on automatic looms at extremely high speeds. Fabric coming from the loom seldom has the perfection of finish and texture that the ultimate user expects; many of the yarns are skewed and patterns are distorted, so these defects must be remedied in the processing of the cloth. The human eye is much too slow to inspect materials at the rate demanded by modern textile practice. The photo-electric cell can do the job nicely, however; the cloth is pulled across a narrow slit illuminated by a beam of light, and the watching cell counts the threads and measures the open spaces which pass the slit. When the cell finds something amiss it actuates a mechanism which straightens the material by changing the forces pulling in various directions.

Textile laboratories are now calling increasingly on physicists to test the properties of the raw materials they use, to devise new materials having desirable properties, and to control production methods and machines. Physics is thus adding greatly to that progress which has enabled the American textile industry to produce as much as four billion dollars' worth of goods in a year. And more and better textiles help produce better weather—at least under the skin.

XV

MAN CLIMBS THE WINDS

To thy speed add wings.
Paradise Lost

FAR above the tracks of a railway crossing the Rocky Mountains, an airplane, a black dash against a gray sky, is smoothly making its way toward the Pacific Coast. In its warm cabin sits a bare-headed young man leisurely conversing with a radio operator at an airport a hundred miles ahead. He is alone, yet the operation of the plane appears to cause him little concern beyond occasional glances at some of the multitude of dials which cover the instrument board before him. There are more than a dozen of these dials, and from each he gleans some bit of information vital to the smooth onward rush of his plane; this dial shows his height above the ground, this the temperature of the oil supplying his engines, those others the rate of smooth turning of the propellers as they bore their way through the afternoon sky. Each of these dials represents the concern of many scientists and engineers that the young man may be unconcerned.

What a marvelous community of co-operating atoms this airplane is! Look for a moment at one of these engines: watch the perfectly timed opening of this valve, the inrush at hurricane speed of air and gasoline molecules sucked in intimate mixture through this hot pipe into the cylinder, the closing of the valve and the maddened battering of the trapped mole-

cules against their prison walls, one of which quickly advances against them; the spark of man-controlled lightning which at the last unbearable moment flashes in the stuffy chamber, precipitating an epidemic of fiery recombination which causes the molecules all to batter a thousand times harder against their prison walls; the moving of the piston wall as it yields before their pressure. Then, after this holocaust, observe the calm opening of the valve, the return of the piston and the retreat before it out the exhaust pipe of the now bedraggled molecules, their energy expended—followed soon by the sucking in of a new charge of fuel and air. And this complete operation occurs in each cylinder not once a second but 16 times; 1000 times a minute, a million times without interruption. Then visualize this same succession of explosions in 16 cylinders, all pushing their pistons at intervals timed exactly to rotate the whirling propeller; and again, two such great engines pulsing together to pull the airplane forward. Yet what is this warm room on wings but an aggregation of some forty varieties of atoms? Assembled and guided by man to achieve smooth, swift flight, each group of atoms is held by nature's laws to its appointed task: here is copper to conduct the flow of electricity, here porcelain to retard that flow; here is steel to resist the expanding forces of hot vapors and transform them into a smooth, steady pull; here are sheets of aluminum to accept the buffeting of the wind and deftly turn each glancing blow into gravity-defying stabilization.

To our grandfathers when young, flying must have appeared to require far more careful balancing than that of the circus equilibrist who, standing on two pedals attached to a single wheel, rides along a tight wire. Yet a modern airplane pilot is less conscious of balancing his plane than a whistling

schoolboy is conscious of balancing his bicycle as he nonchalantly threads his way through traffic with his hands in his pockets. The duty of keeping both bicycle and airplane under control has been entrusted to long-established principles of balance derived from the study of mechanics, the oldest branch of physics. If the laws of balance in motion are obeyed, planes can be designed which will return automatically to equilibrium no matter how expertly mishandled.

Controlling a locomotive requires only that it be made to go faster or slower. An automobile must also be steered, at least horizontally. A bicycle must in addition be kept balanced sideways. But an airplane requires all of these attentions and more. Flying on wings involves three new departures: using power to support weight; steering up and down as well as from side to side; and balancing sideways, and forwards and backwards, at the same time. That these problems have all been solved within a few years so completely that a pilot can, if he desires, turn the entire operation of his plane over to a robot mechanism which does nothing but blindly follow the laws of physics, results from the high stage of development to which this science has been brought.

The four kinds of animals which have preceded man in learning to fly—birds, insects, bats, and the extinct pterodactyls—all have flown by flapping their wings. Man has developed a more efficient method, for he has solved a problem too difficult for unaided nature: that of putting energy into a rotating wheel or propeller. Thus man is able to soar on one pair of fixed wings, while with other rotating wings he pulls his plane forward. Both sets of wings, with their responsibilities thus divided, can be made far stronger and more effective than the wings of any bird, which must be adapted to both flapping and soaring.

2

When soaring flight began seriously to interest inventors, they found the laws of mechanics working in unfamiliar ways. One by one the necessary requirements for stable flight were worked out by various experimenters, but as late as 1902 there was still something lacking. Professor S. P. Langley, a physicist who made notable contributions to flying during the years before 1900, built model airplanes which flew for long distances. Now it is easy to see that his airplanes lacked one essential type of balance control—he provided no way of raising one wing in the air and dipping the other so as to control stability about a horizontal axis in the direction of flight. This is the function of the modern aileron.

The Wright brothers, Orville and Wilbur, became the Columbuses of the air when in 1903 they flew 850 feet in 59 seconds, pulled through space on rickety wings by a gasoline engine of 16 horsepower. Though perhaps not the inventors of the airplane, they were the first to make it practical and the first to fly, and they provided it with the final essential for controlling balance—controls to warp the wings in opposite directions. The Wright brothers, who were shrewd experimenters, studied physics by building a small apparatus—forerunner of the modern wind tunnel—in which they tested the balance and behavior of model airplanes in currents of air.

An airplane is kept in the air by forces quite different from those which "common sense" would lead one to expect. A kite stays aloft when the wind strikes it at an angle, because the molecules of air push against it as they rebound from its

surface, and the combined pressures of countless bouncing molecules furnish sufficient force to balance the weight of the kite. This same force operates on an airplane wing, but in a way which at first sight appears very different. A wing is so designed that air flowing over its top surface must travel farther than that which flows beneath it; and when this is true, the wing need not be inclined at an angle to the horizontal but can even be tilted slightly downward during steady horizontal flight. The physicist, Daniel Bernoulli, found that the faster air flows, the less pressure does it exert on the surface over which it is flowing; by curving the wing the air can be made to exert less pressure on its upper surface than on its under surface. The resultant sustaining force comes most into effect when the flow of air over the wing is in smooth streamlines. When the relative velocity of air and wing falls below what is called the "stalling speed," the air no longer flows smoothly but breaks up into turbulent whirlpools and ripples, with the result that the lift on the wing is greatly reduced. Any method of getting air molecules to move downward after they leave the vicinity of the wing faster than they were moving before they met it, will impart lift to the wing.

The slower an airplane is designed to fly, the larger in area must its wings be made to support a given load; and conversely, sleekness is necessary for speed. Bullet-like racing planes which can exceed 600 miles an hour fall like stones if slowed to less than 100 miles an hour. Small private planes designed to be especially safe, and capable of landing at 30 miles an hour, must be given relatively large wings; and such craft can seldom exceed 75 miles an hour in cruising speed. Most desirable would be an airplane with broad comfortable wings for taking to the air and landing, which could then be

made sleek and narrow for high-speed flying. This is partially accomplished by the trailing wing flap, a small portion of the rear margin of the modern airplane wing which can be turned down to change the flow of air so that a small wing becomes equivalent to a larger one. The flaps are turned down on taking to the air, and enable planes so equipped to leave the ground at speeds only two-thirds of their normal take-off speed. When the plane is slowed for landing, the flaps are again turned down, thus keeping air flowing smoothly across the wings at speeds lower than those at which the plane would otherwise stall.

The airplane wing has been streamlined so that it can be pushed through the air with less than half the power originally required, and has been strengthened until it can carry ten times as heavy a load per square foot as is ever carried by the strongest wing of eagle or albatross. The breaking of a wing on a regular airplane—one that is not being experimented on—is practically unheard of. When a wing breaks off a new type of plane which is being tested, it usually does so because it has started to flutter, building up vibrations of ever-increasing intensity which soon shake the wing so violently that it is torn from the plane.

The weakest parts of the modern airplane, if the truth be told, correspond to the weakest parts of a patrolman on his beat. The constable worries most about fallen arches; airplane designers worry most about keeping the wheels or the landing gear from collapsing under the weight of a giant plane when it strikes the ground. So long as an airplane is moving forward in the air faster than its stalling speed its wings have no trouble in sustaining its weight, but when it is standing on the ground all of its weight is concentrated on two or three wheels. Transoceanic transport planes may rest on each

wheel with a force of 15 tons, and tires for such wheels are often eight feet in diameter, towering far above the top of an automobile. A flying boat can be built much larger and heavier than a land plane, for the load of the resting boat can be distributed evenly over the whole of its broad bottom.

A somewhat paradoxical way to give narrow wings sufficient lifting power to hold a plane in the air at slow speeds is to cause the wings to move through the air faster than the plane. Juan de la Cierva did this successfully when in 1924 he designed the autogyro. He arranged the wings so that they could rotate freely about a post stuck up from the body of the plane, their tips whirling through the air many times as fast as the plane moved forward. A drawback to this idea is that the wing on one side of the ship moves faster relative to the air than that on the other, so it exerts greater lift and tends to tip the plane over. Cierva solved this problem brilliantly by referring it directly back to nature for solution; he hinged the four wings near the shaft about which they rotated, so that each as it moved forward would automatically rise until the lifts on the two sides of the plane were equal. The device is called an autogyro because its wings rotate freely, propelled only by the wind which arises from the motion of the airplane. If the engine, which drives an ordinary airplane propeller to pull the ship forward in the usual way, is stopped, the ship settles slowly to the ground, its whirling wings letting it down more gently than would a parachute of equal diameter.

Cierva was not a cut-and-try inventor. He carefully applied the laws of physics to analyze the forces acting on the rotating wings of the autogyro, and built small models which he tested in a wind tunnel in Madrid. Autogyros can land almost vertically, and can rise more steeply than airplanes of equiva-

lent power. In some recent models arrangement is made to rotate the wings at high speed by the engine before taking off, thus storing up energy which enables the machine to spring straight up from the ground and rise almost vertically. Autogyros have lower cruising speeds than equivalent airplanes, and are unsuited for performing loop-the-loops or other aerial acrobatics; but a "flying windmill" can hover near one spot in a way no ordinary airplane could hope to equal.

Many early inventors had the idea that large propellers might be used to pull aircraft straight up into the air. Unsuccessful helicopters were designed by dozens, but at last they have been brought to the point of practicality largely through the efforts of Igor Sikorsky. With its rotating wings continuously turned by the engine, the helicopter can rise straight up or down, hover in the air, or land in a closely confined space. It has now almost entirely supplanted the autogyro.

¶ 3

PLANES FLYING 4 MILES HIGH have now crossed the 3000-mile breadth of the continent in less than six hours. Even transoceanic planes, great birds weighing 70 tons and with wing spreads of more than 200 feet, now cruise regularly at more than 300 miles an hour. Yet only 37 years have elapsed since an intrepid flyer first limpingly hopped across the continent in 84 days, suffering 15 crackups on the way.

Before World War II the airplane speed record rose 15 miles per hour each year after 1913, on the average. Since then, speed records have risen even faster. The fastest planes can now cut through the air at more than 600 miles an hour

in level flight. Can we expect speeds to continue increasing correspondingly in the future? The power required to keep a plane forging ahead is proportionally greater at high speeds, for the resistance of the air rises ever faster as speed increases. At a certain limiting velocity, tenuous air becomes as hard to penetrate as molasses.

Propeller-driven airplanes will probably never fly much faster than 600 miles an hour. Records of speeds greater than this—sometimes claimed for breath-taking dives when the whole power of the plane is released to plunge it toward the earth—should be taken with a grain or two of salt. Only by the exertion of tremendous forces can air molecules be pushed aside at speeds greater than that with which sound waves course through the air. Sound travels about 750 miles an hour. If I shout loudly, "Here comes a sound wave," the sound "Here" is half a mile away by the time my lips form "wave," yet the fleetest airplane in full flight could cover the same distance in the time required to say, "Here comes a loud sound wave." Engineers calculate that 2000 horsepower is needed for each ton of weight to pull an airplane forward at 750 miles an hour, because such a vast plug of air would be accumulated in front of the plane that the whole immediate atmosphere would need to be moved with it. Nor could such a plane be much more than a flying engine, for the lightest engines now use up the whole ton allowance for each 2000 horsepower they generate.

The introduction during the war of jet engines and of booster-rocket propulsion, as discussed in the next chapter, greatly changed the ideas of engineers regarding possible airplane speeds. By 1949 several pilots had traveled faster than sound, a feat which appeared impossible when this book was first written.

Such high airplane speeds have been made possible by streamlining, dealt with by that branch of physics known as aerodynamics, which concerns the flow of air past solid objects. The principles of streamlining enable engineers to determine what contours an airplane wing, a propeller blade, a locomotive headlamp, or any similar object should have to allow air to slip past it most smoothly and with a minimum of resistance. By modeling a fast-moving vehicle on the lines of a fish, with smoothly rounded front, widest section just forward of the center, and gradually tapering rear, the power necessary to overcome wind resistance at high speeds may be greatly reduced.

At speeds under 50 miles an hour streamlining has little effect, and when applied to automobiles it is largely an affectation, except for psychological value as a symbol of progressiveness. Streamlining railroad trains, which travel at speeds between 60 and 90 miles an hour, has more to recommend it. A train model showed, when tested, that the train to which it corresponded was using a quarter of its total power to overcome wind resistance. Streamlining reduced this resistance by half, resulting in a saving of 12 per cent on power bills totaling millions of dollars when applied to a number of trains.

The streamlining of airplanes is imperative, for, at speeds of 100 miles an hour or over, the drag on a single projection such as a wheel may be sufficient to lower speed by 10 per cent. Three-fourths of the air resistance of one airplane was found to arise from the engine and landing gear. Putting a smooth cowling over the engine of another plane raised its speed from 118 to 138 miles an hour, and gave more effective cooling of the engine. Even the thin wires used to brace the wings, when not removed completely, have been changed

from their original roundness to have a cross section which looks like an undersized minnow.

To study the behavior of airplanes and their parts, such as wings and propellers, wind tunnels are used. A large electric fan blows air through a huge funnel, which concentrates the wind so produced until it howls through a narrow aperture at speeds which in some cases are as great as 1800 miles an hour, ten times as fast as a tropical hurricane. At the throat of the funnel the model to be tested is hung in the air stream. At least one giant wind tunnel can accommodate full-size airplanes up to 45 feet in wing spread. The most efficient wing shape, and the effect on drag of changes in the forms of other airplane parts, can thus be determined directly, without moving an inch off the ground.

In another type of wind tunnel the air is blown vertically, and tiny model airplanes are turned loose in this air stream. Their controls are operated by clockwork, and through windows the designers can watch them spinning or gracefully gliding as they fall freely through a rising current of air. In still other tunnels, refrigerated air is used to simulate conditions in the upper atmosphere when bitter cold may cause ice to form on the wings.

In early wind tunnels the air was allowed to escape after it had blown past the model being studied, but engineers saw no reason to waste all this good breeze, so now they take the outgoing air and pipe it around again into the mouth of the funnel. This gives the modern wind tunnel the shape of a gigantic doughnut, through the hollow body of which tame gales can be made to whistle endlessly.

An additional advantage of the enclosed wind tunnel is that since it can be made airtight, the air in it can be maintained at high pressure, or pumped down to a partial vacuum. In

this vacuum, conditions in the stratosphere can be duplicated to study the behavior of airplanes cutting through air of extreme rarity.

For any particular set of conditions, only one shape of airplane propeller is really efficient. Many and varied were the propeller shapes suggested by eager inventors in the early days of aviation. How different is the long, thin, sleek blade of the modern airplane propeller from the awkward wind spoons of the early planes, or the sails of the Dutch windmill! At the tip of each blade, where the air is cut through fastest, the blade is narrowed and thinned, and the contours are nicely turned to give uniform thrust on the air, with strength where strength is needed. This shape was arrived at after dozens of small models were tried in wind tunnels to see which would "take hold" of the air most efficiently.

It is inevitably true that a given propeller shape is best for only one speed through the air, and for air of a given density. As a plane starts to rise from the ground its propeller should slice thinly through the air; then, when nosing over for a dive, the propeller should be forced to bite more heartily into the air, to prevent it from speeding up in the whine to which we have become accustomed. A practical method of doing this has finally been perfected. The pitch of the propeller—the angle at which it cuts the air—can be altered while it is in motion. Automatic controls are provided which adjust the blades at all times to give the best hold on the air, thus keeping the engine at almost constant speed no matter how hard it may be laboring.

¶ 4

WE HUMAN BEINGS COME HONESTLY by our reputation for restlessness, for, of all the vast store of the earth's energy

which we command, we spend three-quarters in hauling men and materials about the face of the globe. Most of this energy is used, of course, in the transporting of freight, the great bulk of which is carried by steamships and railroads. For human transportation we depend most on the motor car. Twenty-eight million automobiles in America carry people twenty times as far each year as does any other form of transportation—foot, wheel, or wing.

Airplane travel is still an insignificant fraction of all travel. Though wartime developments greatly increased air travel, between 1930 and 1940 people in America journeyed only about one-eightieth as much by air as by rail, and one-twentieth as much by rail as by car. Chiefly responsible for the limited use of flying was unreliability in bad weather, but behind stood the specter of danger. From statistics on passenger deaths one could calculate before the war that air travel, per mile traversed, was roughly 250 times as dangerous as ordinary rail travel, 800 times as dangerous as travel in Pullman cars, and 10 times as dangerous as travel by automobile. All infant transportation systems have passed through such periods of dangerous operation as now beset aviation, and, to a less degree, motoring. Only a few years have elapsed since railroad wrecks sprinkled the front pages of newspapers as airplane wrecks do now. But statistics show that a passenger can expect to fly many million miles before being killed in an airplane accident, and this mileage is being rapidly increased from year to year as the hazards of flying are more thoroughly understood, and as science presents engineering with better tools with which to meet them.

One important factor needed for safer flying is provision of stronger and lighter metal alloys. Great strides have been made recently in the physics of metals—the study of how

atoms cling together to form crystals, and these crystals hang together in metal rods and wires. All metals are permeated by microscopic cracks and flaws which greatly reduce their strength. If only the crystals of which they are composed would hang to one another with the forces with which the individual atoms cling together! Then a cable of steel an inch thick would safely support four million pounds, instead of the mere 300,000 pounds which it now will hold, and that only if carefully made of a number of fine wires twisted together. Lighter and stronger alloys are needed especially for engines, landing gear, and propellers.

In the pure state aluminum and magnesium, though very light, are soft and weak. The metallurgist has now learned how to give aluminum five times its original strength and four times its original hardness; and he has made magnesium alloys almost four times as strong and twice as hard as before. Lithium and beryllium are other light metals which can be used for alloying much more than they now are. The microscope, the spectroscope, and the X-ray apparatus are playing important roles in the development of these new alloys.

Given a strong, light airplane structure with reliable engines, and the weather remains as the chief source of danger in flying. Much worry over weather will automatically be eliminated when planes are developed which are suited to cruising at extremely high altitudes—at heights level with the top of Mt. Everest. Most vagaries of weather do not extend much above 30,000 feet over the earth's surface, so flying six miles up should be smooth and bumpless unless the top of a tropical hurricane is encountered. Ice does not form on wings at great heights, for the air is clear and dry; and prevailing winds are more reliable, though often so high in ve-

locity that planes which attempt to fly against them may find their speed cut in half.

At the heights necessary to get above the weather, the air is only about one-fourth as dense as at ground level, and water boils at a much lower temperature than normal, so new problems of breathing and engine cooling are introduced. Extra oxygen must be provided for engines as well as for crew and passengers. Engines can be taken care of with special iron lungs called superchargers, which force air into the carburetors four times as fast as it would flow unaided; and these have already been developed to permit flight up to altitudes far higher than are needed. High altitude records of more than 50,000 feet have been made with the airplane pilot encased in a special suit and fed oxygen from a tank. Passengers would object to such treatment, so planes are being developed with cabins which can be sealed airtight. They must also be carefully insulated against heat loss to withstand the Arctic cold of the bitter upper air.

If 35,000 feet could be adopted as a standard altitude for cross-continent flying, cruising speeds could readily be increased above 300 miles an hour and a transcontinental or transatlantic trip should require only eight hours. For short hops, climbing to the sub-stratosphere hardly pays: too much time is wasted in going up and coming down.

¶ 5

THE CHIEF OBSTACLE TO SAFE AIR TRAVEL is fog. More than two dozen methods of overcoming fog are now being tested, but none has yet been brought to perfection. All methods involve either clearing the fog away, which is difficult, or avoid-

ing it, which is not always possible, or signaling through it, which alone holds much promise.

To learn how to fight fog scientifically one must first learn what fog is. Particles of typical "pea-soup" fogs have been snared on thin films of grease spread over clean glass plates; under the microscope the individual tiny drops could then be measured and counted. They were found to vary in size from mist particles of pinhead dimensions down to droplets too small to be distinguished clearly even with a microscope.

Long ago physicists found that every drop of water, no matter how small, must have a core, for two molecules of water which chance to bump together in the air cannot stick together—they must have something to stick to. The nucleus of condensation may be a speck of dust, or merely an ion—a molecule which has become charged electrically by picking up or losing an extra electron. In fact, that powerful tool with which physicists make visible the tracks of smashed atoms and of cosmic rays, the Wilson cloud chamber, operates by condensing fog droplets on the ions produced when atomic bullets zip through the air.

The aviator would like to annihilate fog by an inverse process to the one which the physicist uses to make his atom tracks visible. A flier filled with the joy of life on a spring morning has been known to amuse himself by diving his plane toward a small fleecy cloud; then, just before striking it, he pulls up sharply so as to overwhelm the cloud with a gusty blast, under which treatment it vanishes with wraithlike promptitude. Foggy air can be made clear by warming it, either by direct application of heat or by compressing it quickly. Such methods are practicable only with laboratory fogs, however, or with tiny clouds which are already almost at the point of evaporation. Much sterner measures must be

taken to battle a wind-carried North Atlantic fog which blows across half a continent. Fortunately a plane usually can fly above such a fog until it reaches its destination. It is the return to earth which may cause embarrassment.

To sweep fog from a landing field, while expensive, is not impossible. By spraying into the air solutions of chemicals which are hungry for water, a very dense fog has been cleared away in a few seconds when no wind was blowing and no new fog particles were being produced. Even when a high wind was blowing, the spray kept a portion of the field clear as long as it was turned on. This method may prove worth using in emergencies. Burning large fires in long rows down a landing strip was found effective in Britain during the war.

Far and away the most promising methods of handling fog are those which involve letting it alone and learning not to care about it! After all, to learn to see through fog requires only that some type of radiation be employed which will penetrate fog, and that a method be devised of using this.

To measure the fog-penetrating ability of electromagnetic waves of different lengths, physicists have filled long boxes with artificially produced mists, and have sent through, one after another, light rays of different colors, infra-red rays, and radio beams of various wavelengths, observing the fraction of each which emerged at the far end. Usually the longest red rays fared best of the visible rays, but not always; the result depends on how large and how varied in size the fog droplets are. Very long infra-red waves, and still longer ultra-short radio waves, were found to penetrate any sort of fog with ease. Since these waves travel in straight lines like ordinary light, the fog problem would be solved if scientists could make it possible for aviators to see with them.

Ferry boats have pushed their way slowly but safely through

mist-covered harbors when the pilot was able to peer ahead only with a motion picture camera loaded with film sensitive to infra-red rays. With special high-speed methods of development, the pictures were made visible within thirty seconds after exposure; but even thirty seconds is too long to wait to see what is ahead of an airplane moving two hundred miles an hour. The infra-red telescope described in connection with television would give a continuous view ahead which would be up to the minute, but unfortunately this, like the photographic film, is sensitive only to the band of short infra-red waves which can penetrate mist but not a heavy fog.

There are other ways of "seeing" things than by looking at images of them, however, and the aviator needs to know only enough about the positions of objects to enable him to set his plane safely on the ground. The interferometer, devised fifty years ago by Professor A. A. Michelson and long used in physics laboratories for making ultra-precise measurements with light waves, can be used to measure distances as great as two inches to within a millionth of an inch. With an interferometer 30,000 times as big, using waves 30,000 times as long, an aviator could measure distances of a mile to within a fraction of an inch. This principle has been applied with even longer waves in the terrain-distance indicator recently developed by the Bell Telephone Laboratories and the United Air Lines. A small radio transmitter in one wing of the airplane sends short-wave signals which are picked up directly by a receiver in the other wing, and again by this same receiver after reflection from the earth or from any other obstacle in the vicinity. Since radio waves travel with known speed—that of light—the time interval between reception of the direct wave and the bouncing wave measures how far the bouncing wave has traveled. A pilot using this apparatus need make no

elaborate calculations—another dial is added to his collection, and this tells him directly how far in feet he is above the nearest solid object. So sensitive is the device that from nearly a mile above the ground it will measure the heights of buildings and bridges as it passes over them. A radio beam of similar nature can be sent out directly ahead as well, to give the pilot a sensitive finger with which to probe the mist ahead and detect mountains which might lie before him.

Long-wave radio beams are commonly used to keep the airplane pilot on his course, and to give him his directions when lost in fog or darkness. While this method is well developed, difficulties with it sometimes arise when static temporarily interferes with the signals and the radio beam is lost. Short-wave transmitters can be installed near landing fields and arranged to force a needle in the instrument panel of any incoming plane to point directly toward the center of the field. Robot landing apparatus has been devised to take charge of a plane as soon as it intercepts the landing beam, automatically bringing the plane slowly down the beam, and gently applying the brakes after the plane has rolled the proper distance, but this is not yet as effective as might be desired.

Of greater promise than any other method proposed for aerial navigation through fog is radar, discussed in Chapter XVI. Since microwaves penetrate fog without difficulty, a pilot in radiotelephone communication with a landing field can be told by a radar operator at the field just how far away, and in what direction, his plane is at any instant. In this way a plane may be "talked in" over distances of a hundred miles or more. When the plane arrives over the field the pilot can be "talked down" by an observer who can follow him by radar observation.

For all these applications the scientific contribution most needed is some better method than is now available of generating powerful short radio waves—waves only a few inches long, shorter even than those now used for television. Ordinary radio tubes cannot generate such waves efficiently, but new tubes, such as the klystron, and magnetron, hold great promise of providing inch-long waves in abundance.

¶ 6

SOME PERSONS BELIEVE THAT THE AIRPLANE can never be made really safe because it must return to earth whenever its fuel is exhausted. They feel instinctively that a balloon or dirigible, able to stay aloft until its pilot is ready to come down, is inherently much more reliable. Also the dirigible, with its great buoyant lifting capacity, appears to be much more useful for long-distance freight hauling than the airplane. Both these conclusions are open to question.

A dirigible which has used up its fuel waiting for the wind to die down or the fog to clear is a very uncomfortable dirigible to be in, for it is at the mercy of the weather and may be blown out over the ocean. And though no power need be expended to hold a balloon up, in order to be efficient it must be made so large that to push its huge bulk through the air at high speeds requires much power. Even though the danger of explosion can be eliminated by using helium, dirigibles must be made too large for their own good. Their lifting power and strength in the air increase rapidly as they are made larger, but they become increasingly difficult to control when taking off, landing, and being moored in the open.

If dirigibles are to be made really safe, metallurgists must develop alloys light and strong enough to resist the breaking power of the wind on a structure large as a steamship, yet of necessity infinitely lighter. And if safe helium gas is to be used instead of the explosive hydrogen which has caused so many accidents, future airships must be made even larger than present ones.

Strictly speaking, it is not correct to say that a balloon is lifted into the air by the hydrogen or helium it contains. The hydrogen in a large dirigible may pull it down with a weight of forty tons, tons badly needed for useful cargo or fuel. A perfect vacuum in its bag would give a balloon the maximum lifting power, but then the bag would collapse. Filling the bag with gas keeps it distended against the external pressure of the atmosphere, and buoyancy results if the entire weight of bag plus contents is less than the weight of an equal volume of air. Since hydrogen is the lightest gas known, it adds least objectionable weight while keeping the bag distended. But since hydrogen is one of the most explosive of gases, modern designers are turning to the next lightest gas, helium.

A balloon filled with helium can lift about nine-tenths as much weight as if filled with hydrogen. However, half the lifting power is used to overcome the weight of the dirigible itself, with its heavy frame and engines; and so the loss in lift when helium is used may eliminate a good part of the pay load. To restore this requires that the helium-filled dirigible be made even larger.

Helium, long a very expensive gas, is now becoming relatively cheap. Since its atoms are so inert that they combine with those of no other chemical element, helium cannot be obtained from chemical reactions. However, its atoms are produced whenever radium or other such radioactive atoms ex-

plode. Many of these collect and are trapped underground. Gas from some oil wells contains as much as four per cent of helium; improved oil prospecting methods and better methods of separating helium from natural gas are increasing the supply rapidly; and if giant dirigibles turn out to be better freight carriers than giant airplanes, helium to fill them can be supplied.

However, the efficiency of airplanes, too, as freight-carrying devices is found to increase rapidly with size; and since planes are still far smaller and more maneuverable than dirigibles, as well as being several times as fast, it seems probable that the most common type of aircraft of the future will be the airplane. As the airplane evolves it is approaching the contours of a mere "flying wing," a sleek structure with no appendages except the propellers which pull or push it through the air. To increase the speeds of fast airplanes and decrease the power required to propel them, all exposed surfaces are being eliminated which are not actually required to keep the plane moving forward under control. To withdraw various parts into the body of the plane they are being made flat; even flat engines are being designed, arranged to be inserted directly into a fairly thin wing without bulging its smooth contours.

The conquest of the air is far from complete, but a good beginning has been made. Within a few years someone will be flying around the world in three days, taking on fuel in mid-air so as to avoid stops en route. Man knows that eventually he will be able to trust his wings completely; it is only a question of time until dominion over the air will be added to his other conquests.

XVI

SCIENCE IN WAR AND AFTER

Science and peace will triumph over ignorance and war.
PASTEUR

THE tremendous impact of science on human affairs can be seen most clearly in such periods of stress as that during the recent war. Behind the bloody clamor of the battlefield a less evident but more fundamental conflict was taking place—a warfare of scientists and technologists, on which the future course of history depended as truly as on powder and on steel.

Most of the leaders in World War II repeatedly emphasized the importance of science in determining its outcome. Their attitude is exemplified in a statement made late in 1940 by an eminent statesman. "Well," he said, "it looks as if this time it would be up to the physicists to save the world." He recognized that the tide of aggression, which at that time appeared irresistible, might well be turned by one new weapon—a detector to defeat the submarine, or a device to bring down the hurtling bomber. About atomic bombs he had not even dreamed.

That the aggressor nations also recognized the importance of science is shown by their frequent insistence on the existence of "secret weapons." These supposed new developments of science turned out in many cases, fortunately, to be purely psychological in nature, but the V-1 and V-2 bombs

of the Germans were only too real. The limitation on their use, and the eventual defeat of the Axis powers, arose from the fact that leadership in scientific effort had recently been brought across the Atlantic from Germany to America.

Scientific initiative can, for all practical purposes, be considered as non-existent outside of Europe and North America. Japanese and Chinese science has always been imitative, and has shown little evidence of basic understanding on the part of Asiatic scientists. French science, except as represented in a few able individuals, has been decadent for a generation. Russia has been making tremendous efforts to develop both pure and applied science, but is still in the initial stages of this advance. Germany has, until the past decade, held the ascendancy over Britain in matters scientific, but during the recent war British scientists gave an amazingly good account of themselves.

It was in America, however, the "arsenal of democracy," that was found the scientific development which made possible the technological advances which determined the outcome of World War II. In that basic flair for inventiveness known as "Yankee ingenuity" the American has always been without peer. World leadership in fundamental science has been wrested from Germany only since 1918, but in most branches of applied science, particularly in such fields as electrical control, the United States has long been far ahead of any other nation.

The most obvious effect of science on the art of war springs from new weapons, which periodically upset the natural advantage of defender over attacker. Economic and political forces which need adjustment have always existed, but the fact that defense normally has at least a two-to-one advantage over offense leads to stability, and has discouraged the use

of force to settle disputes. When a new offensive weapon becomes available, as when bombing from airplanes added a new dimension to warfare, a potential attacker may be given a temporary advantage.

The defeat of the Austrians by the Prussians in 1866 has been credited largely to the use of the needle gun, an invention of thirty years before to which the Austrians had paid no attention. Other contributions of science which have each in turn encouraged the use of force are the English arrow, the long bow, the cross-bow, the muzzle-loading gun, the breech-loader, and then the rifle, which set elongated bullets whirling so that they would fly faster and straighter toward the mark than would a round shot. Each time one of these devices appeared, the nation which first developed and used it was given a temporary advantage.

Every such new mode of offense is offset, sooner or later, by one or more effective defense measures. In the recent war the magnetic mine, set off by the magnetic field present around any steel ship, led soon to the development of the degaussing girdle, a great loop of insulated wires carrying electric currents which produce a magnetic field to neutralize that of the ship. Discovery of the proper defense measure is sometimes slow, but comes inevitably from the application of scientific methods.

The outcome of almost every battle fought in World War II depended upon the airplane. Air supremacy requires, first, a large number of available planes, but equally important are their speeds and the distances they can fly from their bases without being re-fueled. As each of the warring powers developed new models of fighter planes, that one whose fighters could fly even as little as ten miles an hour faster than

those of the opponent could keep advantage in the air, other things being equal.

In the effort to get every last extra burst of speed into fighter planes, engines are being made continually bigger and more efficient. In propeller-driven planes the power of 2000 horses is released through a mass of metal weighing less than two flesh-and-blood horses, which delivers to the propeller about one-third of the energy in the fuel fed to it. However, the propeller itself is only about 85 per cent efficient, for the tips of its blades travel faster than the plane, and in high-speed planes are moving at speeds dangerously close to that of sound. This sets a sharp limit to the size, speed, and usefulness of propellers.

These facts made scientists and engineers look for other means of pushing planes ahead faster, and the principle of the rocket suggested itself. In this, a concentrated jet of high-speed gas emerges backward from a nozzle, producing a reaction, even in empty space, which forces the rocket forward. During the war period rocket propulsion changed from a laboratory toy to a practical reality, and the first jet-propelled planes made their appearance over the battlefield.

For powering automobiles, motor-boats, or locomotives, rocket propulsion has little value, for it is very inefficient at low speeds. Anyone who has touched off a sky-rocket will remember that a tremendous swish of gases occurs before the rocket starts to move, but as it moves faster and faster the swish seems to "take hold," and ultimately a high speed is attained. The success of the rocket principle was ultimately brought about by releasing the gases intermittently, so that they came out with great force in puffs, rather than continuously. The Germans powered their buzz-bombs very successfully in this way, and most high-speed and high-altitude

planes are now propelled by jets of gas. No matter how fast a plane is moving, rocket propulsion can be used to make it move faster. It is theoretically possible for a rocket to move even faster than the gases which leave it, and these have been made to leave the jet at speeds of several miles a second—many times the speed of sound. Only a super-stratosphere plane flying in the rarefied upper atmosphere could attain such speed, of course, but only rockets could drive it.

Some pursuit and interceptor planes now travel faster than 600 miles an hour on the level, and can rise at the rate of more than two miles in a minute. As higher speeds are approached, distance and staying power in the air become of increasing importance. This makes necessary the use of larger planes, capable of carrying enough fuel for greater distances than the four or five hundred miles of which a small plane is capable. Once this greater size has been achieved more of the load capacity can be used for guns and armor as well as for fuel. Instead of a single pilot who operates one machine gun shooting between the blades of the propeller, as was common during World War I, a larger plane carried as many as eight men, with a dozen machine guns and several small cannon. It became possible also to encase such vital points as the engines and the pilots' and gunners' compartments with steel armor of sufficient thickness to resist machine gun bullets. The plane then began to justify the term "flying fortress," and even though it might travel at not more than 300 miles an hour, it could easily fend off the attacks of small fighters buzzing around it at much greater speeds, and soon shake them off as they had to return one by one to their bases for re-fueling.

Though the trend is toward even larger battleships of the

air than the famous B-29 "Superfortress," there is a limit to the weight of airplanes that can alight on land. When a 70-ton bomber is on the ground its entire weight must be supported on its wheels, and these are large and unwieldy in the extreme. Pontoons rather than wheels will avoid this problem, and it seems likely that the giant flying battleships of the future, if such there must be, will rest on water when not in the air.

2

DURING THE FIRST FEW MONTHS of the aerial bombardment of Britain in 1940 the German bombers seemed invincible, but gradually the fundamental truth, that for every new offense there is a satisfactory defensive answer, was borne out. First came the defeat of the day bomber by the pursuit plane, and when losses during each daylight raid rose to 10 per cent, the Germans were forced to restrict bombing operations to the hours of darkness, when pursuit planes could not find the bombers.

Several months passed during which night bombing raids were the most pressing problem facing the British, but gradually hints began to appear which indicated that a solution of the night-bomber problem was imminent. At the end of 1940 the Air Chief Marshal announced that a method for frustrating night bombers had been found, and in June of 1941, the basis of the method was made public. It was the radio-locator, later to become famous as "radar," and this, widely publicized as Britain's secret defense weapon, gives an excellent example of the use of science in defensive warfare. As far as an enemy bomber is concerned the device is used to turn night into day. If no light waves are available to see with,

says the scientist, look around for some other type of waves.

Actually nature perfected a similar method of detecting night fliers long before the airplane was dreamed of. For hundreds of years bats have been able to fly about in pitch-black caves without colliding with each other or with obstacles in their paths. Scientists have stretched numerous criss-cross wires in a room, and then darkened the room completely before bats were brought into it, yet when the bats were released they flew blithely about without once striking against a wire.

Careful tests showed that the bats were indeed flying blind, for when adhesive tape was placed over both eyes a bat could avoid the wires quite as well as with its eyes uncovered. Though the proverbial bat may be blind, it can steer at high speed quite as well as any sharp-eyed lynx.

When adhesive tape was placed over the ears of the bats, however, the results were very different—the uncanny power disappeared completely. Similarly were they handicapped if the power of hearing was restored, but their mouths were taped shut.

Scientists found that the bats were constantly broadcasting high-pitched squeaks during flight, sounds so shrill that only occasionally could an unusually low one be heard by human ears. These sounds were quite audible to the ears of the bat, and can of course be detected by special microphones. When several bats were set flying around a dark room in which only the flutter of skinny wings was audible to the crouching scientists, the microphone detectors showed the air to be filled with a shrill clamor of very short wavelength—a super-sound related to ordinary tones as ultra-violet light is related to visible light. The human ear cannot hear waves vibrating faster than 20,000 times a second, but the bat lan-

guage used for aerial navigation is found to be loudest at 50,000 vibrations a second.

As a blind man walking along a sidewalk keeps tapping with his cane to produce sounds which will be reflected from walls and other obstacles, so the bat keeps broadcasting his shrill cries and these, reflected from other bats, walls, or even wires, come back to his sensitive ears and warn him of danger ahead.

Though these super-sound waves will do very well for the navigation of bats, or even of boats, they would be of little help in steering airplanes in the dark, for these waves move no faster than ordinary sound waves, and we have already seen that a fast airplane flies at two-thirds of this speed.

Far more effective for this purpose, and capable of being used in the same way that bats use super-sound, are radio waves. These travel nearly a million times as fast as sound waves, and since airplanes fly only about ten times as fast as bats, this gives ample margin, providing science can furnish a means of responding to the reflected wave which is about 100,000 times as fast as the response mechanism of the bat. This rapid response mechanism scientists have now been able to develop.

To detect something with waves it is necessary that the waves used be not much longer than the object being detected. Therefore, to locate an enemy bomber having a wing span of 100 feet, one should use waves not much more than 100 feet long. Other factors make still shorter waves desirable, and radio waves only a few inches long, which we have already met as micro-waves, are found to solve the problem admirably.

What an effective picture of the secret maneuverings of science this presents! Here we have German planes loaded with destructive bombs, five miles up in the air, swiftly feeling their way toward London by following a beam of radio

waves sent from a station behind them in France. Such beam flying has of course been used for years, and is a commonplace feature of most airlines in peacetime. But how is the bomber to know when to drop its destructive cargo? From Norway or some other point making a wide angle with the first beam another radio beam is sent, directed to intersect the first beam directly over the target. When signals in his earphones tell the pilot that he has reached this intersection, he drops his load of bombs and turns to streak for home. Scientifically designed murder, to be sure, but this is not the whole story.

Scattered all over Great Britain were short-wave radio stations which sent beams of micro-waves toward the invasion coast. When the sky above France was clear of planes no waves were reflected to the sensitive receivers which the British kept constantly on watch. But when a plane rose into the air even 100 miles away, it reflected back some of the micro-waves, and thus could be detected in ample time to let interceptors take the air and be ready for it.

Radar was officially given the credit of having enabled the Royal Air Force to win the first defense of Britain, and make possible the turning of the tide of war. The blind bombing of German cities through dense clouds by the Air Forces of the United States Army was made possible by fitting their bomb sights to use radar. The battles in the Coral Sea and elsewhere, in which many Japanese vessels were sunk by smaller groups of American vessels, went the way they did because, in the dark of night, the Americans could "see" by means of radar where to shoot, while the Japanese, with less effective radar sets or none at all, could not. All during the war German and Japanese scientists were working feverishly to improve their radar outfits, but at no

time did they even approach the perfection of equipment attained by American and British scientists, who worked in close co-operation.

¶ 3

THERE ARE TIMES when a new type of camera is more important to an army than a new type of gun, and when a good photographer is of greater value than an able sharp-shooter. Before and during an intensive campaign dozens of planes may fly over the enemy lines every day without dropping a bomb or firing a shot. These planes contain complex oversized cameras with which pictures of the terrain are taken, to detect any changes in its appearance since the previous flight. The eye of the camera has a great advantage over that of any human observer, for not only can it absorb an entire scene in a few thousandths of a second, but it brings back a record of what it saw which is permanent and far more revealing, when examined slowly and in detail, than the most lingering glance of an observer in an airplane. Films taken on two successive days can be superposed in such a way that differences between the two—a departed ship, a freshly bombed oil-tank, or newly camouflaged artillery—will stand out vividly from an unobtrusive background of details common to both photographs.

Reconnaissance planes are as vulnerable to attack as any others, so they must fly as fast and as high as possible. Great altitude requires provision of giant cameras, weighing several hundred pounds and costing more than $5000 apiece, with very large lenses. To take a photograph from a height of several miles which will reveal details as small as a man requires the use of a lens consisting of four to six carefully shaped pieces of the finest glass, each as large as a dinner plate. Such

a camera is, in fact, a telescope of sufficient size to delight the heart of almost any astronomer. To provide a shutter big enough to cover such a lens, which can yet open and close within a few thousandths of a second, requires careful scientific designing.

When flying a reconnaissance plane, a pilot must be prepared to level off at some definite height and fly a long, straight course while photographs are being taken. When a red light starts blinking on his instrument panel, the pilot knows that he must fly the ship on an even keel so the photographer can snap mile after mile of enemy territory, taking several hundred pictures on a single roll of film. Automatic timers are sometimes used, which click the shutter at any desired regular interval. It was common knowledge in 1941 that every day hundreds of miles of the "invasion coast" of France was thus photographed by the Royal Air Force. From some of the planes used for this purpose pictures were taken at an altitude of more than five miles. By using multiple cameras in which each click of the shutter took nine pictures through as many lenses, an area as great as 900 square miles was photographed with each exposure.

The greater the altitude from which photographs are taken, the more likely is the ground beneath to be partially hidden by haze. Light scattered from this haze changes what would otherwise be a crisp and vivid picture into one of dull uniformity and low detail. Longer waves than those our eyes can see will be less scattered by the haze, and for this reason infra-red photography has become of great importance in modern warfare. But longer exposures are required when the specially sensitized film needed for infra-red exposures is used, as we have seen in a previous chapter. For this reason all the armies of the world have been concerned with the development of infra-red film of increased sensitivity.

As enemy territory becomes more thoroughly protected by fighter planes during daylight hours, it becomes increasingly difficult to take the desired reconnaissance photographs each day. Therefore, the trend is toward more night photography, when darkness lends to planes increased safety from antiaircraft fire and aerial pursuit. Thus flashlight photography has been brought into warfare, but flashlights on what a scale! Instead of filling with light a small room or even a huge auditorium, the flash must illuminate the whole of outdoors!

To make an area of many square miles as bright as day, even if only for an instant, army photographers have developed amazing flashlights which consist of great sacks full of magnesium powder, wafted slowly to earth by small parachutes. When the photographer wishes to take a picture, he merely tosses a sack of the powder over the side of his plane. The parachute with which the sack is provided opens automatically, and a fuse is set off which explodes the bomb a few seconds later, after the powder has had time to fall the desired distance below the plane, and has lagged sufficiently behind it. A blinding flash of light comes from the exploding powder, and the first light from this flash strikes a phototube on the plane, and immediately opens the shutter of the camera. Events are automatically timed so that the shutter opens just as the landscape is most brightly illuminated.

Camouflage—the art of concealment by merging an object with its surroundings, or by making it appear to be what it is not—requires increasing cleverness if it is to withstand successfully the searching eye of the camera. An oustanding example of this occurred in July, 1941, when the British published photographs showing how the Germans had attempted to mislead them into bombing an innocuous block of houses in Hamburg instead of the great railroad terminus which the

British were seeking. A bridge over a narrow body of water pointed directly at the railway station, and this the British airmen had been using as a landmark. The ingenious and industrious Germans covered the offending body of water as far as the bridge with rafts carrying false houses, and a short distance away installed a false bridge which pointed at the block destined for sacrifice in place of the station. This device might have succeeded had not the superposition of photographs taken before and after the alteration revealed the shift.

The stereoscopic camera, with two lenses giving a pair of photographs which, when viewed properly, merge into one which has depth and a lifelike appearance of solidity, is especially valuable in revealing camouflage of a common type. On developing photographs of a certain enemy flying-field, British officers found that something looked queer about a group of airplanes packed closely in one corner of the field. The planes looked ordinary enough when viewed from the air, and in the usual photographs, but when a stereoscopic camera was used they appeared quite flat and lifeless in the resulting views, instead of sticking up from the ground as they should. It is not difficult to imagine the feelings of the soldiers who had diligently fitted together boards in airplane shapes, laid them on the ground, and painted them, when next day a lone bomber, sailing over on the way to deeper-lying territory, carefully dropped two wooden bombs on the field.

Of great value in detecting camouflage of another sort is color photography, but strangely enough, ordinary color photography often is not so useful as partially color-blind photography. Certain commanders were surprised to find that one or two of their aerial observers were able to detect four times as many camouflaged objects behind the enemy lines as most

of their observers could see. Tests showed that the abnormally sensitive observers were color-blind.

The explanation was not far to seek. The camouflaged objects had been carefully painted by soldiers with normal vision, who had matched their paints in color with the surrounding green foliage. The color-blind observers, however, could not see green anyway. The greenness which, to a person of normal vision, obliterated lesser differences between paint and foliage, was eliminated in their eyes, leaving contrasts of redness or blueness or tone or shade to stand out vividly.

This discovery caused many articles to be published stating that color-blind persons would be in great demand as aerial observers. Such was not the case, for although it is impossible to give normal color-vision to a person who is color-blind, it is quite easy to give artificial color-blindness to any person with normal vision. All that is needed is to equip him with a pair of colored glasses which will absorb light of the color he is not to see. A pair of magenta lenses will make him green-blind, for no green light can traverse them, while blue lenses will make him red-blind. Such colored glasses have indeed been found of great value in aerial observation, and the really scientific camoufleur should use a spectroscope to be sure his paints match the foliage for any light waves that may strike them. To make the match complete with surroundings, he must include the invisible ultra-violet and infra-red waves as well as those which the eye can see, for the eye of the camera can see several octaves of color, whereas the human eye can see but one. By using the proper color filters on his scientifically equipped camera the aerial photographer can ferret out any object in which all colors, invisible as well as visible, have not been closely matched with those of the surroundings.

4

THE TANK, introduced by the British during World War I and since developed by other nations into a formidable juggernaut, is the modern scientific equivalent of the armored knight of the Middle Ages. Because spices had to be used instead of refrigerants to keep meat palatable in those days, and because nothing was known about balanced diets and vitamins, the medieval knight was rather a stunted fellow by modern standards. Most of the suits of armor preserved in museums are found to fit men less than five feet six inches tall.

Even the most colossal knight would not have been strong enough to carry armor of sufficient thickness to withstand modern high-power bullets, however. To be sure, he could clothe himself and his staggering horse in heavy armor, but once dislodged he became powerless. What more reasonable than to substitute an automobile for the horse, use tractor treads to cover rough ground at high speed, and put the armor on the resulting tank instead of on the man?

The tank, like the airplane, is undergoing a period of rapid engineering development, with scientists concerned principally in making its armor tougher and more resistant to penetration. The larger a tank is made, the more powerful can its engine be, and the greater the proportion of its weight which can be used for defensive armor and offensive armament. A bullet an inch and a half in diameter was formerly big enough to punch holes in a tank, but now shells three inches in diameter are necessary. Thus 7-ton light tanks must give way to 25-ton

medium tanks, which in turn retire before the great 80- and 100-ton tanks now being introduced.

There is a limit to the concentration of weight which soil can hold, however, and if the weight of a tank is to be increased its treads must cover a larger area. But the larger the tank the less strong does its unwieldy bulk become. Like the dinosaur, too large a tank is impractical, and may ultimately collapse of its own weight. For this reason the battleship of the land can never expect to compete with the battleship of the sea, which, like the whale, is supported in depth as well as in area. Land tanks weighing 200 tons may become practicable, but to hold 40,000 ton tanks, a liquid is the only suitable medium.

On the sea, armor plate can really come into its own, and a solid two-foot thickness of the toughest steel can be used to make an almost impenetrable barrier. The resulting battleship spends most of its life in harbor, or cruising about merely existing as a threat to lesser vessels, waiting for the few minutes or hours when it may be in action. Then precision of fire is of the utmost importance, and the fate of a whole navy or nation may depend on the extra thickness of a hair by which the muzzle of a 16-inch rifle is elevated. The enemy is to be struck if possible before his shells can strike back; no useful development of science which will bring this about is considered too expensive.

Between 1911 and 1941 the biggest rifles used by the navies of the world swelled from 12 inches in diameter to 17. This made possible the hurling of tons of steel 28 miles instead of a mere 11, with a vast increase in accuracy. No navy expects to hit its target at the first salvo, which must be considered as several thousand dollars spent to find out how the wind is blowing and how accurately certain intricate calculating ma-

chines have been used to determine range and direction of aim. In the better navies the target is supposed to be struck on the third salvo, but the second is becoming increasingly useful as better scientific methods of measurement are brought to bear on the problem.

To hit a target 30,000 yards away requires careful determination of the speed of both vessels, the angles of pitch and roll of the ship, the barometric pressure, the humidity of the air, and even the temperature of the powder loaded into the gun. To introduce all these factors involves extensive computing which, if done with pencil and paper, would require days to complete. Instead, great computing machines are used on which the temperature of the powder can be set in with one crank, humidity with another, range, speed, and the rest of the factors with others; then the wheels turn and the correct setting of the guns is calculated automatically within a few seconds.

Before the calculating machines can be set into operation, careful measurements must be made with a dozen scientific instruments, and of these the range-finder is perhaps most interesting. This has the difficult task of measuring the distance to a target, which may be anywhere from half a mile to thirty miles away. A modern range-finder may contain 1600 parts built with the utmost precision, and may cost as much as $40,000. In it are glass prisms whose sides are so true that if one were extended a distance of 80 miles, the line would be within a foot of its correct course. A modern battleship is likely to have at least four of these instruments, with two smaller ones pointed into the air to determine the heights of airplanes.

There are several types of range-finders, but most involve a principle similar to that involved in telling how far away an

object is by looking at it with both eyes open. Look at your finger held six inches from your nose and your two eyes will be turned in sharply; now look at something far away, and the eyes will turn so as to look in almost parallel directions.

If human beings had eyes set farther apart in their heads than they now are, we would be able to judge distance more accurately than we now can. In the range-finder the two eyes may be placed as much as thirty feet apart, by using prisms to bend the light rays. Two telescopes are set into opposite ends of a long tube, and the light which comes through these is sent by prisms and lenses into the two eyes of the observer.

One of the telescopes always looks straight ahead, but the other can be swung through an angle to look at any object at which the other telescope may be pointed. The observer sees his target magnified as in an ordinary telescope, but everything above the middle of the image has come through one telescope, and everything below through the other. He can turn a handle until the two parts of the target come together into one well-fitted picture; then both telescopes are pointed directly at the target.

The turning of the handle also operates a computing machine, which works out the mathematics involved in finding how far away an object is when the lines of sight of the two telescopes make a certain angle. The distance to the target can be read directly from a dial which gives the correct answer no matter where the handle is set; thus ranges up to 40,000 yards can be read quickly to within one salvo pattern.

Range-finders are usually placed high above the deck of a battleship, to enable them to peer over the bulge of the earth at distant objects. That the guns are many feet below the range-finders, and must be pointed high into the air rather than directly at the target, while they rock from side to side

as the boat rolls and pitches on the waves, does not disturb the mechanisms charged with the duty of landing the first salvo close to the target.

¶ 5

EVEN AS EARLY AS 1935, Hitler had turned the major attention of German scientists to the search for new developments useful in war. As his threat developed other nations began tardily following suit. In Great Britain the demand of the armed services for physicists and chemists became so great in 1941 that these key scientists were not permitted to enlist as soldiers, but were drafted for laboratory work. A great shortage of trained scientists soon developed in all the warring countries.

Recognizing that the most powerful weapons of offense and defense are furnished by science, the man in the street, particularly in America, attempted to do his bit as an inventor. Between 1918 and 1938 a Naval Consulting Board in Washington is said to have received 110,000 letters containing suggestions for improvements in naval defense, and a National Inventors Council was set up by the United States government in 1940, to aid inventors who wished to make suggestions. Some of the ideas received were rather amazing, but a sufficient number to justify the effort of the board of experts who sorted them out were said to have merit.

Much of the time of such experts could be saved if more laymen understood the difference between an invention and an idea which represents the desire to make an invention. An idea which was probably suggested more frequently than any other during the recent war will serve to illustrate. This involved a device which, when struck by sound waves from

an airplane flying overhead, is supposed to rise into the air, automatically follow the airplane by measuring the intensity of its sound, overtake the plane and blow it to bits. This is a grand idea, and the inventor of such a device would deserve the eternal thanks of all men of good will. Hundreds of well-intentioned Americans, to say nothing of numerous citizens of other countries less imbued with the inventive urge, consider themselves to be the inventors of this device, and if anyone ever succeeds in making it work will surge forward to claim their just reward. They do not realize that the idea of building so useful a defensive device does not constitute an invention—it is the idea or group of ideas that will make the device operable that is important.

When practical difficulties are pointed out, it is easy for the amateur inventor to fall back on the assumption that these can be eliminated in "hundreds of ways." He realizes, quite correctly, that it should be possible to fasten on the device a pair of microphones some distance apart, and connect them in such a way that they will indicate from which direction a sound wave is coming. It is a simple matter, for example, to put a pair of microphones on opposite sides of a motor-boat and arrange them so that the boat will automatically steer itself to follow the engine noises from another motor-boat. It is quite another matter to do the same thing in the air at speeds twenty times as great.

Another difficulty usually overlooked is the fact that sound waves travel only slightly faster than a fast airplane can dodge through the sky, and the listening device will hear sounds coming, not from where the plane is, but from where it was when the sounds were emitted. It would be quite easy for a clever pilot to set such a device chasing its own tail.

Another favorite field of amateur inventors in wartime is

the "death ray," but this is a device on which scientists waste no time whatever. All that is needed to make a death ray usable is the discovery of a suitable ray. None of the agencies known to physicists at the present time is one-thousandth as effective in destructive action as the shell or bomb containing a powerful explosive, demolishing what it strikes by the impact of matter on matter, and the rapid release of energy near the point of impact.

An explosive is a substance in which everything needed to produce a violent reaction in which a great deal of heat energy is liberated, is present. A fuel can release its energy only by combining with oxygen from the air. Gasoline is not an explosive but a fuel, because it needs oxygen to burn with—a mixture of gasoline vapor and air is a violent explosive, because the oxygen is at hand. Yet many fuels contain more energy than do explosives—for example a pound of gasoline or a pound of butter, if properly mixed with a few pounds of oxygen, contains as much potential destruction as seven pounds of dynamite.

A very violent explosive can be made by mixing pure finely divided carbon powder with liquid oxygen. This device is periodically "discovered" by some new inventor who brings it to the attention of the armed forces. It has been used for years in blasting operations, and makes a very safe type of explosive, for the carbon and oxygen can be kept harmlessly apart until just before the explosion is to take place. Bombs filled with this material can be made more destructive than many now in use, but the difficulty is one of practicality and convenience. Liquid oxygen requires heavy machinery for its production, evaporates very rapidly, and is difficult to store and carry around. Many of the new and most destructive chemical explosives are merely less violent but more prac-

ticable approaches to this ideal of pure carbon and pure oxygen.

In selecting a practical explosive, other considerations besides violence enter. In addition to the amount of energy set free in the explosion, the rate at which the energy is released is important. Safety in storage must also be considered. The great discovery of Alfred Nobel was that nitroglycerin, whose molecules are so delicately balanced that a slight shock is sufficient to start them rearranging their atoms to release the heat which is the basis of the explosion, could be made much more stable by mixing it with clay or sawdust. Thus dynamite was invented. Trinitrotoluol, or TNT, which is made from toluene which is in turn obtained from petroleum, is a very violent explosive which can be pounded or squeezed quite safely. This insensitivity to shock makes it excellent for use in explosive shells, which get quite a blow when fired from a gun.

The violence of all previously known explosives was as nothing, however, compared to that of the atomic bomb, first made practical in the summer of 1945. During World War II new chemical explosives were developed, but these were only three times as powerful as the gunpowder invented 600 years before. The atomic bomb brought violence at least 12,000 times greater than that produced by the most powerful bomb filled with a chemical explosive.

With the atomic bomb as an offensive weapon, and defense revolving around automatic radar-aimed antiaircraft artillery to shoot down bomb-carrying aircraft, the next war will obviously involve a new level of frightfulness if it is allowed to occur. It now becomes possible, however, to make most of mankind aware of this fact, and for the first time there appears to be a real chance that the force of circumstance may compel men to learn to dwell together in peace.

XVII

THE ATOM YIELDS POWER

Knowledge is more than equivalent to force.

SAMUEL JOHNSON

EINSTEIN'S Relativity has long stood in the popular mind as a typical abstruse theory, plumbing philosophic depths of the universe but of little practical importance. Yet one of the predictions of this theory, that matter and energy are so interchangeable that when one is destroyed an equivalent amount of the other will appear, led to an event which practically stopped a world war overnight. Though they had already lost the war, the Japanese government was assured by the atomic bombing of Hiroshima of being able to convince its own people that the time for surrender had come. At the same time the announcement that atomic energy had really been released, and on so terrifying a scale, caused the civilized world to pause and consider.

It was as long ago as 1905 that Einstein brought forth his famous formula revealing the equivalence of matter and energy. If any quantity of matter were destroyed, he said, it would turn into an amount of pure energy which could be calculated by multiplying its mass twice by the velocity of light. From this it turns out that a pound of coal, which on being burned will give out less than ten kilowatt hours of heat energy, if transformed completely would give out a billion times as much. Nor would it be necessary to use coal; garden dirt or sugar or any other material would do, for all

matter is made of atoms, and Einstein's formula applies to atoms of any kind.

Such speculations were the origin of the lurid journalistic statement made frequently during recent decades, that there is enough energy in a cup of water to drive an ocean liner across the Atlantic. This is actually an understatement. A few drops of water, or grains of sawdust or anything else, contain enough atomic energy to drive the *Queen Mary* from Southampton to New York. The trouble was that neither Einstein nor any other scientist knew how to release this energy.

In the middle of 1945 the world learned that scientists had succeeded at last in releasing a part of it. Only a small part, to be sure—less than one part in a thousand of the energy contained in its atoms was released in the atomic bomb, and that from only atoms of the heaviest, most complicated, kind; but the first step had been taken. Whether all the energy in an atom can be set free remains to be seen. Mankind will be well occupied for a time, however, in taming the first violent output.

Physicists have long known that heavy complex atoms are likely to be unstable and to blow up suddenly, releasing energy as they shoot out various types of rays. The radium atom, for example, has been contributing energy to commerce in a small way for many years. Fifteen cents' worth of radium, mixed with a fluorescent powder whose molecules emit light when struck by rays from exploding atoms, when painted on the hands and dial of a watch will produce enough light to enable one to tell time in the dark without difficulty. The amounts of energy thus released are very small, however. Also radium is scarce, and the steady rate at which its atoms explode is not controllable.

A uranium atom is considerably less likely to explode at

any given instant than a radium atom, but it will explode sometime, and it has long been known that energy is spontaneously released from uranium atoms. No means of getting energy out faster was known, however, and the amount involved was extremely small. Now a different, more controllable, process of releasing energy has been found, and uranium can be used as an atomic fuel. The new discovery appears likely to start an age of atomic power which will dwarf both the steam and the electrical ages.

During World War I, Sir Ernest Rutherford was attempting to learn how to release atomic energy at will in his laboratory at Cambridge University in England. He fired alpha particles at nitrogen atoms, and by knocking chunks out of their cores was able to transform some into oxygen atoms. Rutherford was not able to bottle any man-made oxygen, however, for he converted only a few atoms, and would have had to alter at least two million billion to collect enough material to work with chemically.

When James Chadwick, a British physicist, discovered the neutron in 1932, a very satisfactory missile for shooting at atom cores became available. Since neutrons have no electric charge, they can insinuate themselves through the electrical barriers which surround all atomic nuclei better than can charged particles such as protons or electrons. We have already seen in Chapter IX how ordinary atoms, when bombarded with neutrons, may become artificially radioactive and unstable. Neutrons of various speeds, from those moving listlessly to those darting with the speed of a proton which has fallen down a two million-volt electrical precipice, are given off in profusion from the cores of exploding atoms, and can then be used to cause other atoms to explode.

Within the year preceding the outbreak of World War II

the German physicists Hahn, Frisch, Meitner, and their collaborators announced discoveries which showed that neutrons could make atoms blow up at will, releasing very large amounts of energy. Hahn bombarded a small chunk of uranium with slow neutrons, and found that barium appeared to be created. Meitner, who had previously carried on similar experiments, suggested that in Hahn's experiment the core or nucleus of each uranium atom struck was being broken down into two nearly equal fragments which became the nuclei of two new atoms, one of barium and one of krypton. In this "fission" process the uranium atom exploded with a two-hundred-million volt electronic bang, releasing far more energy than was put into it by the neutron.

Enough was known at that time about atoms and their ways to indicate that the atom which could thus be made to release millions of times as much energy as was put into it was not one of ordinary uranium, but of a rare kind of light uranium, of which only seven atoms are to be found in a thousand atoms of natural uranium metal.

Thus was laid the groundwork for secret experiments on atomic explosives which were carried out during the war by the leading belligerent powers. In 1940 discussion of the release of energy from uranium disappeared quietly from the news, and a secret scientific race for time began. As things turned out, the outcome of World War II hinged more on radar and other scientific and technological developments than on atomic bombs, and the democratic nations won out on all counts, but atomic research started by the enemy only a few years earlier might have turned the scales the other way. The United States government learned in 1940 that a large government laboratory in Berlin had been set aside entirely for research on uranium. The British government knew

in 1941 that in Norway several pounds of heavy water was being produced each day, turned into chemicals suited to producing atomic bombs, and then delivered to Germany. Knowing well that the war might end in Allied defeat in a few weeks if the Germans learned how to release atomic energy before the Allies did, the British sent commandoes to blow up the heavy water plants. Anyone believing that the discoverers of the atomic bomb should have hurled their accursed find into the ocean to save the world, would do well to talk with government officials who passed many worried months wondering whether the enemy, hot on the trail of atomic explosives, would reach the goal first.

¶ 2

ATOMIC, OR MORE PRECISELY, nuclear energy is released by super-chemical reactions just as simple as the reactions taught in high school chemistry, but involving atom cores instead of molecules. Ordinary chemistry deals with the shifting of atoms from one molecule to another to form new molecules; nuclear chemistry deals with the shifting of protons and neutrons from one atomic nucleus to another to form new atoms. This difference can be seen easily by looking again at the various levels of matters shown on pages 110-111. We are dealing now with the tiny hard core or nucleus, which contains most of the mass of the atom, and all of its positive electrical charge.

Looking at the levels of matter and the various kinds of energy associated with them, one can see why a nuclear explosion is so much more violent than an ordinary chemical explosion involving molecules. Molecular energy is more

superficial than atomic energy because molecules are made of atoms. By bending his bow, an archer can store enough energy to send an arrow more than a hundred yards. If he were to burn the bow, many times as much energy would come out of the molecules of which it is composed, and by bottling the hot gases he could send the arrow much farther. By carrying the process on one step more, penetrating into the very atoms of which the molecules in the bow are composed, and releasing some of the energy in the nucleus of each atom, he would be tapping basic energy itself—the deep, underlying sea of energy of which our physical universe is composed. On this sea, ordinary chemical energy represents only ripples and waves, while elastic energy stored in a drawn bow is merely a fleck of foam. It is the fundamental energy whose slow release keeps the sun and the other stars hot, and hence everything in our world warm.

Uranium, the first atom to yield its energy to man in large and controllable quantities, is the heaviest of the atoms occurring in nature, and the most complex. It is found to be a mixture of three kinds of atoms, all having cores with 92 units of positive charge, but differing in the number of neutrons contained, and weighing respectively 234, 235, and 238 units. It is convenient to refer to these as U-234, U-235, and U-238. The first occurs in nature in only minute quantities, and hence is not important for the production of nuclear energy. Most uranium atoms are of the U-238 type, and these are of great importance as basic raw material in one of the atomic energy processes. The most direct process for releasing atomic energy involves U-235. This has a nucleus containing three fewer neutrons than U-238, and is found to split up with a tremendous burst of energy when an extra neutron shot into it finds a likely spot and sticks.

To release nuclear energy on a practical scale it is necessary to set up a "chain reaction." In this a neutron penetrates a U-235 nucleus, which splits, releasing energy and neutrons; these penetrate other U-235 nuclei, releasing more energy and neutrons; and the reaction builds up as fire spreads through a piece of paper. If paper is very wet a flame will not spread in it; similarly, unless U-235 is extremely pure, the chain of neutron production dies out. Chief difficulty in keeping the chain reaction going is to provide U-235 free, not only from other chemical elements, but also from its atomic twin U-238, which absorbs neutrons without contributing new ones.

Most impurities can be separated from U-235 by chemical means. Not so U-238, for since the two kinds of uranium are alike chemically, ordinary methods of chemical separation blindly dump both into one hopper. To separate the two species of uranium, known as isotopes, it was necessary to develop on a large scale special methods which had previously been used only in the laboratory.

Uranium is not the only material which consists of isotopes. Most of the chemical elements have within the past few years been found to consist of more than a single type of atom, the various types differing only in the structures and weights of their nuclei. For example, mercury atoms are found which weigh 196, 198, 199, 200, 201, 202, and 204 units each, yet they all have 80 positive charges on the nucleus, and 80 negative electrons arranged in a standard grouping around it, so all are mercury. These isotopes, like others, are indistinguishable by ordinary chemical means, and to separate them it is necessary to use refining processes which make use of the differences in weight of the nuclei.

Many years ago Sir J. J. Thomson removed electrons from neon atoms by ionizing them, sent the resulting ions hurtling

over an electrical cliff in a vacuum tube, and by blowing them sideways in electric and magnetic winds found that they separated into two groups. One group had nuclei weighing more than the other, though all had the ten units of nuclear charge which stamped them as neon atoms.

While this method had worked beautifully for separating a few thousand atoms, it did not at first seem promising for large scale use in separating uranium isotopes. Dr. E. O. Lawrence and his collaborators at the University of California in 1941 developed new methods of ionizing uranium atoms in a vacuum, however, and swinging them through curved arcs with the strong magnetic field of a large cyclotron. As in Thomson's experiments, the lighter atoms skittered further sideways in the field than the heavy ones, and by putting tiny buckets behind slits where the two kinds of atoms struck the wall of this "mass spectrograph" they were soon able to collect pure U-235 at the unheard-of rate of nine millionths of a pound per week, or a pound in twenty centuries. That this was hailed as an encouraging achievement shows the difference in magnitude of atomic experiments on the scale of individual atoms and those involving ounces and pounds. The results were encouraging enough to set Lawrence to work with a giant 15-foot magnet and other improved apparatus, and he was ultimately successful in producing relatively large amounts of pure U-235.

Other processes for purifying U-235, which were operated on a large scale in Tennessee during the war, made use of the differences in the rates of diffusion and distillation of the uranium isotopes. Previous experiments with hydrogen, the lightest of all atoms, gave valuable guidance in developing these methods. All hydrogen atoms had been supposed to be alike until Dr. Harold C. Urey discovered heavy hydrogen,

which brought him the Nobel Prize of 1934. Urey had wondered whether a heavier kind of hydrogen atom might not exist. He reasoned that since the nucleus of a hydrogen atom is known to consist of one proton, there might be another kind of hydrogen containing one proton and one neutron in its nucleus, and weighing twice as much.

The easiest way to detect heavy hydrogen atoms, Urey decided, would be by means of the spectroscope. Using the Bohr theory of the production of light by atoms, it was possible to predict the exact wavelengths of the light which would be emitted by an atom weighing twice as much as the normal hydrogen atom, yet having the same chemical properties. In particular, the new hydrogen should emit a spectrum line slightly displaced from a very bright red line which is emitted by ordinary hydrogen. With a large grating spectograph Urey took photographs of the light emitted by gas taken from an ordinary commercial tank of compressed hydrogen, and in the first photographs he and his assistants found, in addition to the strong red line, a faint spectrum line in the expected position. But the line was extremely weak, and to make sure that it was real they must in some way get a higher concentration of the heavy atoms used to produce it.

One way to concentrate this heavy hydrogen, Urey reasoned, would be to liquefy a large amount of ordinary hydrogen and let this evaporate in vacuum. The molecules formed of two ordinary hydrogen atoms, being lighter, would be expected to boil away faster than those composed of two heavy atoms. In collaboration with workers at the National Bureau of Standards Urey collected residues from large quantities of evaporated hydrogen. Then a small amount of this was put into a glass tube which was placed before the slit of a spectroscope, and excited electrically like a neon sign, and a picture

was taken. Sure enough, the previously faint line was now much more intense, and heavy hydrogen had definitely been discovered.

Later Urey and other experimenters were able to concentrate heavy hydrogen until it was almost completely free of ordinary hydrogen, and it is now produced as an article of commerce. One hydrogen atom out of every 7000 in nature has been of this heavy variety since long before science began, but no one knew it until Urey thought to reveal the heavy atoms with the spectroscope. Now "heavy water" is made by combining heavy hydrogen atoms with ordinary oxygen, and this is finding valuable uses in the release of atomic energy, and in many chemical and biological processes. The diffusion and other separating processes developed by Urey and his collaborators were also applied to the separation of U-235 from U-238.

[3

A METHOD OF RELEASING nuclear energy involving the new, man-made element called plutonium is probably destined to be even more important than the fission of U-235. Atoms of ordinary uranium, U-238, can be turned into atoms of plutonium, which is quite as good atomic fuel as U-235. Plutonium atoms are not found in nature in sufficient quantities for detection, for they blow up spontaneously and only a few exist at any one instant. Since the plutonium process uses U-238 as a raw material, and since 140 U-238 atoms are found in nature for every U-235 atom, this process increases the amount of nuclear energy available from natural uranium more than a hundredfold over the U-235 process. Equally important, plutonium, being a different element from uran-

ium, can be separated from it by ordinary chemical means. The U-235 occurring naturally in uranium aids the conversion to plutonium, so there is no reason to separate it by using the slow and expensive isotope methods needed when U-235 is the desired material.

The basic steps in the production of plutonium are simple. Some of the U-235 atoms present in a chunk of uranium are struck by neutrons produced by cosmic rays or stray radioactive rays, are thereby split, and release new showers of neutrons. Some of these neutrons are absorbed by U-238 atoms present, which then change into U-239, another isotope of uranium, which does not occur naturally because it is not stable. The nucleus of this atom soon breaks up, emitting a negatively charged beta particle, and so becomes a new nucleus having 93 positive charges, or one more than uranium. Hence it is the atom core of a new element, called neptunium because Neptune is the planet in the solar system which lies just beyond Uranus. The neptunium atom is in turn unstable, and soon ejects another beta particle from its nucleus, turning into a still different atom with a nuclear charge of 94. This is an atom of plutonium, so called because the planet Pluto lies next beyond Neptune.

The actual operation of converting uranium into plutonium is carried out in great piles of uranium blocks, now referred to in the nuclear power "industry" as "piles" or "reactors." The uranium pile is likely to be one of the great engineering devices of the future. With no moving mechanical parts, but filled with countless flying neutrons, cracked atom cores and other atomic particles, this vastest of all atom-smashing devices can be made to give off thousands of kilowatts of power, and in its normal operation heats appreciably the water of a great river like the Columbia.

The primary purpose of these large piles is not production of power, however, but of plutonium. That power is produced incidentally adds many engineering difficulties, for means must be provided for carrying away from the inside of a pile the tremendous quantities of heat generated. Calculations show that a pile which would produce a pound of plutonium in a day would release about 500,000 kilowatts of power, or enough for the needs of a good-size city.

In addition to uranium, a pile contains graphite or some other "moderator" to slow the speedy neutrons emitted by the splitting U-235 atoms to the speeds most favorable for sticking in a U-238 nucleus. Any one of several light materials, such as the hydrogen in heavy water, or beryllium, or carbon serves admirably, for all will slow the neutrons down without absorbing them too strongly. If a fast neutron passes through slightly more than a foot of graphite it will be slowed to about the right speed for capture by a uranium nucleus.

So that the greatest number of uranium atoms will be exposed to the densest swarm of neutrons moving at the best speeds, the uranium bricks in the pile are arranged in a lattice structure, among blocks of very pure graphite. Purity is of the utmost importance in everything connected with the pile, for even ordinary traces of impurities will "poison" the pile by furnishing atoms of types which absorb neutrons, and thus prevent them from striking uranium atoms. Certain materials, such as boron and cadmium, are particularly "poisonous" to the production of neutrons, and use is made of these to hold down the rate of reaction of a pile in operation.

Since neutrons which shoot out of a pile cannot affect any uranium atoms, and the larger the pile the more chance there will be of a given neutron striking a uranium nucleus, there

is a certain minimum size below which a particular type of pile will not operate. Theoretically, the best shape for a pile would be spherical, but a great ball of uranium and graphite weighing many tons, which must be taken apart periodically, is difficult for engineers to construct, so most piles have been either shaped like doorknobs, or made merely rectangular.

A number of experimental piles were set up during World War II in physics laboratories at Columbia University, the University of Chicago, Los Alamos, New Mexico, and elsewhere. It was on December 2, 1942, that the first pile went into operation, at the University of Chicago. Instruments for measuring the number of neutrons flying about were inserted at strategic points within the pile, and these were watched carefully while the uranium blocks were piled up, and the "moderator" for slowing down the neutrons between the blocks was added. Cadmium rods were kept in the pile to absorb neutrons, should too many be generated, and these could be pulled out slightly at any time to see if the chain-reacting build-up of neutrons was ready to start. The operator of these rods was like a man with a watering pot, setting a pile of excelsior on fire in his study wastebasket, keeping it properly dampened to prevent the flames from spreading unduly.

On that winter day in 1942 a man-made nuclear reaction first became self-sustaining. Gradually the neutron density built up as the cadmium rods were partially withdrawn, and soon the pile became gently warmer as it gave out half a watt of power—less than the smallest electric lamp. Ten days later, after making sure that the atomic fire would not get out of hand, the rods were withdrawn further and the pile was allowed to generate 200 watts—enough heat to keep an electric iron gently warm. Later, in the great piles built in the West

for plutonium production, power outputs of thousands of kilowatts were reached.

No throttle on a steam or gasoline engine was ever so simple in principle as that which controls the reaction rate of a giant pile. A group of boron steel rods placed at strategic positions in the pile are put under the control of electric motors, which in turn operate in response to the indications of neutron counters. If the neutron density inside any part of the pile rises beyond the desired level, the neutron counter causes the electric motor to push the corresponding rod in further, more boron atoms are set to absorbing neutrons, and the rate of atomic transformation is cut down.

Offhand one would suppose that a pile could be kept running until most of the U-238 atoms in it had been converted to plutonium. This could then be separated by chemical means and used in an atomic bomb, for operating a power plant, or to produce curative rays for use in medicine. Secondary reactions which take place while the pile is in operation prevent this, however, for these produce new types of atoms which absorb neutrons. Thus internal poisons are manufactured within the pile, and the chain-reaction is ultimately slowed down. It is then necessary to shut off the pile, cool it, take it apart, and after the plutonium has been separated, re-purify all the materials going into it, before it can be started up again.

The operation of a pile and the separation of the final atomic fuel is not so simple as it sounds, however, for while the pile is in operation it gives off vast clouds of radioactive rays, invisible but none the less dangerous to personnel, and corrosive to all near-by materials. An operating pile must be surrounded by thick walls of concrete or other absorbing material. Even the atmosphere is affected by the rays emitted,

and air-tight shields must be used around the pile. Removal of the uranium slugs containing plutonium must be carried on by automatic machinery, and they must be dissolved in acids and pumped by remote control from one chemical tank to another. No person can go near a pile in operation, and even the water used for cooling must be held for a time in special ponds to allow it to lose radioactivity before it returns to the river.

When the plutonium has been separated it is ready for use as an atomic fuel. All that is needed is to bring together a sufficiently sizable mass of plutonium, and the chain reaction, started by a stray neutron, builds up until tremendous amounts of energy are released in the form of heat. This may be instantaneously, as in an atomic bomb, or slowly, as in the original pile, depending on how rapidly the neutron density is allowed to build up.

4

To THE EXTENT that we can profit by similar, though lesser, developments in the past, we are justified in speculating on the future of nuclear power. The first naive reaction to the news that the fundamental energy of the universe has been tapped is to wonder optimistically whether we now have any further use for coal and oil. The next reaction, when some of the difficulties are made apparent, may be to underestimate the new development, as was done by those who predicted that the automobile would never really compete with the horse, and that the airplane would always be too dangerous for public use. Both types of reaction ignore the fact that the work done on nuclear power during the war period, though costing two billion dollars, involved only a few preliminary

steps, which will inevitably be followed by many others.

Since great quantities of power are needed to prepare nuclear fuel, some persons think of the precess as merely one in which large amounts of energy are concentrated in a very small bulk of matter. Under these conditions our new knowledge of the atom helps solve the energy-storing problem, but gives us no new useful source of power. However, less energy actually goes into the preparation of a spoonful of plutonium than comes out when its atomic energy is released, and even this energy is required merely because of the present inefficiency of the purification process. This efficiency can without doubt be increased many times further.

Will atomic power ever be available for operating locomotives, airplanes, automobiles, kitchen stoves and sewing machines? Attempts to answer such questions at present are speculative, but Yes seems more likely to be a correct answer than No, if we think of the power as coming from large installations rather than from plutonium pellets. As to when we may hope to buy an automobile with enough atomic fuel sealed in its mechanism to propel it for its entire lifetime, a sensible guess might well be "A very long time." To make available such a "fuelless" car would require, among other things, the development of better shields for nuclear radiations than the several feet of concrete now required.

Freed nuclear energy appears as heat. This suggests its use to operate a steam or vapor engine, or turbine, or some form of jet propulsion. Steam engines have never been very satisfactory in the small forms needed for automobiles, while jet propulsion has its greatest value in airplanes. Perfection of such engines will require solution of many new problems in chemistry, metallurgy, and engineering. Parts must be designed to operate at high temperatures without corrosion

while being bombarded by intense atomic rays. In addition scientists must worry about the protection of living beings from these rays. Yet so great are the possibilities of science that we cannot doubt that these problems will be solved, though predictions as to the exact form of the solution are dangerous.

Once satisfactory engines have been devised, the problem arises of releasing energy in them at the desired rate. This should be easier to solve than the problem of making an atomic bomb explode, for it is usually easier to slow down a reaction than to speed it up. If the energy of plutonium can be released in millionths of a second, as is necessary in a bomb which must not be allowed to blow itself apart before all its energy has been released, it should be possible to release it over weeks or years. This is already being done in the great uranium piles, which can be made to simmer atomically at any desired low rate by adjustment of the control bars which govern the release of neutrons.

It seems probable that new reactions for releasing atomic energy will be discovered, making other minerals than uranium ores available as sources of atomic fuel. Protoactinium and thorium, atoms next in complexity to uranium, can be made into atomic fuels by methods already known. The former is so scarce as to be not worth considering, but thorium is quite abundant. At present its use is less advantageous than that of uranium, because the neutrons used to cause the thorium nucleus to split must move rapidly instead of slowly, so they are more difficult to concentrate in the necessary numbers.

The possibility that U-235, plutonium, or thorium will replace coal and oil as industrial fuels within the lifetime of any living person may be dismissed at once. New types of

power displace old types but slowly, and almost never replace entirely those still available—it is said that far more firewood is used now as a fuel than ever before in history. The electric motor did not eliminate the steam engine, nor did the steam engine do away with the horse, which is still bred in large numbers. There is as little likelihood that atomic engines will displace steam and gasoline engines and electric motors in the next fifty years, as that the airplane will eliminate the steamship or the freight train. Competition there will undoubtedly be, and the industrialist should not emulate the livery-stable proprietor who was too proud to turn garage operator.

Thus the world finds itself with a new instrument to be used for good or evil, and timid souls feel as their ancestors did when the first firearm was demonstrated. Will the world be at the mercy of any person of evil intent who chooses to make use of the new power? The checks and balances which arise rapidly to hold in reasonable bounds each new development of this sort, and keep it from disturbing the progress of civilization in too fundamental a manner, are hard to see in the first new glare of discovery. One can be comforted somewhat, however, by remembering that though in theory no one is safe in a streetcar because he might be shot by an evil person carrying a gun, actually most human beings manage to live out the better part of threescore years.

XVIII

THE END IS NOT YET

Still o'er the earth hastes opportunity,
Seeking the hardy soul that seeks for her.

JAMES RUSSELL LOWELL

IT is characteristic of beginning scientists to fear that the most important discoveries have all been made in the past, and that the most useful devices have already been invented, leaving only lesser problems for further ingenuity to attack. That the day which will mark an end to new discoveries is still far off should be apparent to anyone who considers the course of research and invention.

The research physicist pulls matter and energy to pieces to see how nature is constructed; the applied physicist puts the pieces together again in new combinations useful to man. The first process results in discovery, the second in invention, which in turn often leads to further discovery. How many useful new combinations of matter and energy—companions to our incandescent lamps, radio receivers, X-ray machines—can still be devised depends greatly, of course, on the fertility of imagination of the applied physicist and his fellow scientists; even if all fundamental research were to stop tomorrow many important inventions could still be made, for forty years or more often intervene between the advent of a discovery and its first application to useful ends. But even more than on inventive genius, progress in applied science

depends on the supply of fresh materials—new molecules, temporary atoms, penetrating rays—which the research scientist is able to furnish for use in new inventive combinations. It will be a long time before physical discovery, and hence invention, must cease because all that can be found out about the structure of matter and energy is known.

It is, of course, impossible to estimate how much remains to be discovered regarding physical entities of which we as yet know nothing, the future equivalents of the neutrinos and mesons and other sub-atomic particles which have been discovered in such bewildering numbers during the past two decades. An indication of needed discovery can be obtained, however, by considering what is lacking in our knowledge of that portion of nature which is already partly in our ken. Our ability to convert energy directly from one form to another may be taken as one simple measure of progress.

When an electric circuit is formed by twisting together at their ends two pieces of dissimilar wire such as iron and copper, and one junction of the wires is heated more than the other, an electric current begins to flow in the circuit. Here, obviously, is a method of transforming heat energy into electrical energy. Conversely, if a battery is used to send a current of electricity through the two wires forming the circuit, one junction will get hot and the other will be cooled. In this case, electrical energy is changed to thermal energy. Dozens of such methods of transforming energy have been discovered.

It is instructive to make a table of such energy conversions by arranging across the top of a page headings designating all the known forms of energy—mechanical, thermal, acoustical, chemical, and so on—which, though all expressions of the three fundamental forms electrical, magnetic, and gravitational, may here best be entered as used in practice; and

then listing these same energy forms down the side of the page. We may think of these rows and columns as labeling bins in which devices which convert energy from the form of the row to the form of the column may be deposited. When a research physicist discovers a new method of transforming energy, we may think of him as depositing a new device in one of these bins. Thus when Michael Faraday in 1831 found how to change mechanical energy into electrical energy, his discovery went into the appropriate bin, and at once it became possible to design the dynamos which equip all our electrical power stations. Some of the bins will be found to be quite full; that containing devices for converting mechanical energy of one form into mechanical energy of another form will contain the pulley, the screw-jack, the lever, and numerous other machines. But no matter how long one spends in filling out such a table, some of the bins will remain empty. So long as any bin lacks an entry research physicists are justified in trying to fill it, for no one can tell when some applied physicist or engineer, searching for a way to accomplish some end quite as important as aviation or telephony or television, may find himself unable to proceed because no suitable method of transforming energy is available.

Consider a simple problem which has actually arisen. An inventor wishes to record photographically the forces which are exerted on various important parts of a railway locomotive as it clicks over rail joints, lumbers across switches, and sways down long mountain grades. He realizes that this can be accomplished most easily if he can translate the forces into electrical form, for then he could send these through wires to a laboratory car inserted in the train just behind the locomotive tender. He looks in that bin of our table which should contain devices for converting energy from mechanical

to electrical form. Will he find anything? In this case he is lucky, for several possible methods are available. He selects the piezo-electric effect as being most suitable for his present need, and imbeds quartz crystals at various strategic points in the locomotive; one he buries in a spring clamp, another he tucks away in the axle housing of a huge driving wheel, a third in a coupling; finally sixteen have been disposed of. Each of the crystals translates into electrical form the mechanical forces which are applied to it, and the resulting signals are impressed on sixteen cathode-ray oscillographs in the laboratory car. By photographing on moving film the vibration patterns on the oscillograph screens, a continuous record can be kept of the stresses and jerks occurring in the anatomy of the locomotive. From this the railway superintendent can learn at the end of a run how each vital element of the engine was strained and pounded throughout the trip.

It is obvious from such a table that many energy transformations cannot now be made directly; sometimes they can be made by changing first to an intermediate form of energy and then later to the desired form, but this is often inefficient. Many of the empty bins will surely some day be filled; whether all of them can be filled remains to be seen. If past experience is repeated even new forms of energy will be discovered, new rows and columns added to the table.

12

FOR EVERY QUESTION that a good research physicist can answer, he can ask two questions whose answers he would like to know and which he intends to learn as soon as he can extend his investigations. With so much remaining to be dis-

covered, and with so many clues to possible discoveries visible on every hand, a career in fundamental physics now offers great attractions to youth. Nature yields her secrets regardless of age; in fact, most of the great discoveries in physics have been made by men who had not yet reached middle life. Newton made his most important discoveries before reaching the age of thirty, and many of his successors have done likewise. Nature repays full well those who are possessed of enthusiasm, curiosity, and eagerness for learning her secrets; and in physical research there is little necessity for recourse to tradition and authority. When any argument can be decided by experiment—by asking nature the answer—age has the advantage of experience over youth, but certainly not of authority.

The scientific method of settling an argument, which is already having a profound effect on our modern culture, is in marked contrast to that used of necessity in previous years. Sir Richard Gregory quotes the attitude prevalent in a past century regarding a student who insisted on maintaining his own opinion: "If he does not believe the statement of his teacher—probably a clergyman of mature knowledge, recognized ability, and blameless character—his suspicion is irrational and manifests a want of power of appreciating evidence." In former times knowledge, ability, and character were the chief indicators of truth, even in science. Though we may agree that these qualities are of more fundamental importance than scientific knowledge, any branch of learning, in which the only method of determining a fact—say the distance from the earth to the moon—is to take the average of the guesses of a hundred men of knowledge, character, and ability, no one of whom knows how far away the moon is, is decidedly limited. A member of a majority of the Supreme

Court is never wrong in legal matters, because, in the absence of higher authority, it is necessary to call him right by definition. A scientist need never be called right by definition, because he has the priceless heritage of working in a field where truth itself can be uncovered.

How much more truth must be uncovered before physics can be said to have set its house completely in order is best made evident by attempting to find, from physicists or from books on physics, the exact answer to some particular problem concerning the probable behavior of matter and energy in a given situation. For example, it is important for chemists who wish to predict the formation of molecules from atoms to know the amount of energy stored in an atom when its electrons are arranged in some particular configuration. This information can be obtained most conveniently with the spectroscope, and for many years spectroscopists have been working patiently to accumulate the necessary data on atom after atom. Yet when a chemist today selects an atom at random—say platinum—and asks for a particular energy value, the chance that he can be given a definite answer is still less than fifty per cent. Learning how to find the structures of atoms is only a beginning; the task of determining the structures of atoms is still less than half done. To expedite this task, further invention is needed—invention of new measuring and computing machines which will handle great masses of large numbers with accuracy and dispatch.

A similar situation to that involving atomic structure holds throughout the entire body of physical knowledge, and it is during the routine investigations concerned with filling obvious gaps in our knowledge that those new, unexpected discoveries which so delight the scientific soul—things that men didn't know they didn't know about—are made.

Take, for example, the Compton Effect. Dr. Arthur Compton set out upon a perfectly routine job of investigation that needed doing—seeing how X-rays would be scattered from a chunk of matter, just as some previous scientist had investigated the scattering of light from rain drops. Quite unexpectedly, Compton found that some of the waves of the X-rays were changed in length when they were scattered, and this discovery at once made obvious a great many things which were happening in the world of atoms and electrons. Part of Compton's reward was the Nobel Prize in 1927.

Max Planck, in 1900, tried to work out an explanation of why pieces of matter which are heated to high temperatures should emit more light of one wavelength than of any other, and less light at both longer and shorter wavelengths. No explanation of this phenomenon could be made, he found, except by supposing that light is emitted by atoms not as continuous trains of electromagnetic waves but in the discrete bundles of energy which we have discussed as photons and which he called quanta. Thus the Quantum Theory was born. For many years few people paid any attention to it; yet within three decades this theory was found necessary to explain the behavior of photographic plates, the conduction of electricity through wires, the conduction of heat through walls, the behavior of photo-electric cells, and the manner of emission and absorption of light by atoms and molecules. In fact, the entire structure of modern physics and chemistry, and therefore of all the natural sciences to which they are fundamental, rests upon it.

Planck's discovery, like those of X-rays, radioactivity, and the electron, came at a time when some physicists felt that the days of great physical discovery were over. They were wrong, and since that time no informed scientist has felt need to

worry about a lack of things to investigate. The rate of discovery is constantly increasing. It is still as true as when Edward Everett Hale said it—"There is no end to truth, no boundary to its discovery and application."

13

THERE ARE DOZENS OF DEVICES whose use would greatly benefit society, yet which are at present not available because some relatively simple requirement concerning matter or energy cannot be fulfilled—because some key word is missing in the crossword puzzle whose solution will bring greater control over nature. As an example of a problem whose solution is vital to future human welfare, yet is retarded by lack of the type of fundamental information which only research can give, rather than by any lack of human inventiveness, let us return to a subject discussed briefly at the beginning of this book—the possibility of tapping new sources of energy. This problem is a favorite one with amateur scientists and inventors, but few such have made any progress in its solution, for most of them have attacked it only superficially.

Since all wealth springs from energy, development of new sources of power seems to be an easy road to riches. That there is great demand for power, especially in electrical form, is obvious; between 1920 and 1930 the use of electric power doubled in the United States, and now two-thirds of all dwellings in this country are wired for electricity. The power they consume feeds ten million electric toasters, twenty million electric irons, thirty million radio sets, and more than a hundred million incandescent lamps. Much more power than is used by all of these together, however, goes to produce mag-

netic fields in electric motors, which set into rotation wheels that drive trains, lift elevators, saw wood, turn lathes, and do countless other mechanical jobs for the industries of the nation. Nine-tenths of all energy used by man is spent, in fact, turning wheels.

About one-third of the 120,000,000,000 kilowatt hours of electric power produced in a recent year in the United States was developed from water power, the other two-thirds being produced from coal- and oil-burning plants. The water flowing over Niagara Falls (or more correctly, the water which does not flow over the falls, since it is by-passed through turbines) generates 1,500,000 horsepower, which would cost $360,000,000 a year if all delivered to our homes at current domestic power rates. Hoover Dam can provide even more energy, being rated at 1,800,000 horsepower.

Since mining coal costs money while water power appears to be free if one happens to own a waterfall, it seems offhand as though electric power generated at a waterfall should be cheaper than that generated by burning coal in a steam plant. A water-power plant must be built near a waterfall, however, while a steam plant can be operated economically at any place to which coal can be hauled cheaply; and at present it is much more expensive to send power over wires in electrical form than it is to ship it in chemical form as trainloads of coal. There are large coal-burning power plants even near the brink of Niagara Falls. The highly concentrated solar power supplied by waterfalls is not so free as it looks.

The same argument applies in even higher degree to the harnessing of the tides. To be worth while this must be done on an extremely large scale; and even when a whole bayful of water can be impounded at high tide and made to operate turbines when the tide is low, energy must be stored to pro-

vide a continuous flow of power. This requirement usually adds so much to the cost of the project as to make it economically unsound.

Another pastime of amateur inventors is to attempt to devise methods of harnessing the vast energies of the winds. These energies come directly from sunlight, but wind power is even less concentrated and dependable than tidal power. A few attempts have been made to improve the efficiency of windmills; several large mills have been built which will produce 100 kilowatts of power—three dollars' worth per hour retail, or sixty cents' worth wholesale—when the wind blows. To make them worth operating, however, the wind would need to blow most of the time.

Inside the earth there is a vast reservoir of heat energy, and many engineers have dreamed of tapping this. Sir Charles Parsons, famous inventor of the steam turbine, suggested boring a shaft twelve miles down into the ground, through which water could be piped. Steam could then be brought up by other pipes, and with it steam engines could be operated. In common with most grandiose schemes for tapping new sources of power, this would cost so much for installation and upkeep that it would probably be far cheaper to put the money spent on it in the bank and buy coal with the interest. Steam comes naturally from crevices in the ground in Italy, in Finland, and in California, where it is caught in boilers and used to run engines; but noxious and corrosive gases often come mixed with such steam, and it usually costs more to remove them than to generate the steam by burning coal.

All of this sounds very discouraging, but since the energy involved in these schemes has come originally from the sun, cannot something be done to harness sunlight directly?—not

through agriculture, but by means of energy transformations which would convert light into, say, electrical power.

Glancing over a table of energy transformations like the one discussed in a previous section, we find several involving light which might be useful. There is the Peltier or thermo-electric effect, for example. Sunlight might be allowed to fall on one set of thousands of junctions between copper and iron wires, while the other set of junctions was cooled by water, and the current so generated might be used to charge storage batteries. Unfortunately this process is as yet very inefficient; a whole square yard of the most suitably chosen junctions delivers only a few mousepower instead of the expected horsepower.

Then there is the photo-electric effect—not in the photo-electric vacuum tube, in which light merely controls the flow of electricity from a battery, but in the barrier-layer photo-cell, in which light actually produces electric power. This process also is very inefficient; there is, however, some hope that when understood its efficiency can be increased. When more is understood about photo-electricity it may be possible to build cells which will deliver useful amounts of power. If this can be done, engineers may cover the southern slopes of desert mountains with acres of shallow glass-covered black trays, designed to soak up sunshine and deliver electric power. If the process could be made even ninety per cent efficient, an area equal to that covered by a small dwelling could generate one hundred horsepower on a sunny day. At present, however, the efficiency is so low that less than one-tenth of a horse-power would be realized from such an area—one-third of a cent's worth of energy per hour.

The simplest method of using solar energy, and at present one of the most efficient, is to soak up sunlight directly with some black surface and put the resulting heat into a boiler.

Several steam plants for generating power from sunlight in this way are now in operation, but these are curiosities or hobby displays rather than actual commercial installations. In some of them sunlight is concentrated on a blackened boiler by means of mirrors, which are of course expensive and fragile, and require frequent cleaning. If focusing mirrors or lenses are used, they must be kept turning to keep pace with the apparent motion of the sun. After the novelty of such equipment wears off it is usually found cheaper to buy and shovel coal than to keep the apparatus in repair; and when the sun sets or goes behind a cloud, coal must be shoveled in any case, for it is not feasible to generate power for public use unless it can be stored, or delivered whenever the customer wants it.

It is of course conceivable that some clever inventor may devise a solar steam plant which will be cheap enough and efficient enough to justify its existence, but it is more likely that scientists and engineers will solve the problem by systematic attack, if it is to be solved. To be sure that the sun would shine even half the time, the plant must be installed in a desert region; and desert regions at present furnish little market for power. The solar-energy problem is therefore closely involved with the cost of sending power over long distances. Devise an economical method of sending electric power more than three hundred miles and there will be greater value in devising solar engines. Again, the problem of utilizing sunlight is intimately connected with the storage of energy, for the sun will continue to set at night, and unless power is to be piped half around the earth some means of storing energy during the day for use at night must be provided. More information is wanted on how energy can be stored.

Whether the world of the future derives its motive power from sunbeams, from the atomic nucleus, or from these plus the refinement of present sources of power, it will be an interesting world. Man holds within his hands the power to make that world virtually what he will. In particular, one of the bits of wisdom he is slowly learning in his gradual climb is that nature need not be accepted as she is at the moment, but can be smoothed out over a period of time and over an area of space, to make the ups and downs of life less severe.

¶ 4

Discussion of the responsibility of science for ills of the human race, of which the miseries of war are at present most striking, is to a considerable degree academic. We cannot be rid of science if we would, for science is, after all, nothing but knowledge, and it is doubtful that the human race has the ability to keep itself in everlasting ignorance, even if this should be proved desirable. Few persons would argue that ignorance *is* desirable, but many point out that man's spiritual development has not kept pace with his material progress. This is obviously true, but blame for the situation can as justly be attached to the slowness of spiritual development as to the rapidity of material progress. Actually, of course, the difficulty arises from the fact that spiritual development comes only from human experience. Nature provides an automatic compensating mechanism, such that if material progress is too rapid, suffering results which accelerates spiritual progress.

Most of the clamor against science arises, not from real worry about spiritual development, but because it is human nature to take benefits for granted, while complaining loudly

against accompanying disadvantages. It is of value to pause and note how easily these disadvantages are exaggerated.

Much of the horror of modern warfare arises from the fact that hundreds of millions of people, through the agency of radio, motion pictures, and the daily press, are brought far closer in imagination to the battlefield than was ever possible before. Though more people do suffer as a result of warfare nowadays, a larger proportion of them suffer only mentally and in anticipation.

Science, with its improved methods of communication, is responsible for the fact that the number of things we find to worry about is increasing from day to day. Science is, however, also responsible for the fact that there is an even more rapid increase in the fraction of these terrible things which never happen.

There was a period in the development of the modern radio receiver which is illustrative of our reaction to present world events. When radio sets had been made extremely sensitive, so that they would respond to far-distant stations as well as to those close by, a great deal of adjusting of knobs was necessary to bring to proper loudness the speech or music issuing from the loud-speaker. Otherwise, distant stations were weak, while those close by were overwhelming. To eliminate need for this close attention, automatic volume control was devised. With this the response of the radio automatically adjusted itself to give a normal output level of sound from signals no matter how weak.

This method produced excellent results, but it had one serious drawback. Whenever the radio set was tuned to a wavelength on which no signals were coming, the obedient electrons, in their efforts to work up the proper volume of sound, would so amplify all the bangings and cracklings of electricity

with which the air is always filled that the irrelevant signals of static would be magnified out of all proportion. To overcome this effect many modern radio receivers are arranged to lose sensitivity entirely except when tuned to some desirable signal.

It seems likely that the news-gathering sources of the world need such an arrangement at the present time. They are now in the condition of the half-developed radio which, if it can find nothing else to deliver, brings in static with the same flourish that it bestows on the most important programs.

The War of 1812 went on for several weeks before the contending navies knew that peace had been declared. Today, if desired, one can learn within five minutes or five seconds of an event that has occurred anywhere on the surface of the earth. As we read our evening papers or listen to a broadcast of the news, we have turned up the automatic volume control in the radio of world events until it is difficult to distinguish signals from static.

Science does not make war more terrible, it merely makes it seem more terrible, which is a very desirable result. Actually, it is no worse to be killed or maimed by an atomic bomb dropped from an airplane than by a great rock pushed over a precipice by some savage neighbor of ten thousand years ago. We are constantly seeing more clearly the futility of wars which, with the aid of science, are becoming ever more dramatic in a constantly shrinking world.

But, one could argue, surely more people are killed in a modern "scientific" war than were killed in wars held during the days when men struck each other with clubs or impaled each other on lances. In absolute numbers this is true, but relative to the number of living persons it is not true; the evidence shows that through the ages wars have become progres-

sively less bloody in proportion to the numbers of persons living.

In 1800, only 148 years ago, Robert Fulton predicted that the time might come when England would hold as many as ten million souls. Today there are several times this number, and in normal times room for many more. This room is available only because science has shown how to increase the available nourishment and means of livelihood, thus removing bars to the growth of population. More than two-thirds of the people living in civilized countries can thank science that they are alive at all, for without modern machinery the world could not support them.

There are now two billion people alive in the world. Of these, more than thirty million die each year, in war or in peace. Modern war is responsible for directly adding less than 1 per cent to the human death rate. Modern science is responsible for diminishing that death rate by more than 60 per cent; the fact that the average life expectancy at birth in Europe or America is approximately sixty years instead of the twenty years it was a few centuries ago means that the annual death rate averages 16 per thousand instead of 50 per thousand.

During late 1940 the average number of persons killed in Great Britain by bombs was about 5000 per month. This number shrinks somewhat when one realizes that during normal times of peace, more than ten times that number die in an equal period. Thus the bombings might be expected to increase the death rate temporarily by as much as 10 per cent. However, the actual statistics show that even this was not the case, for during the twelve-month period from July, 1940, to July, 1941, the death rate in Britain actually declined below that of peace times. Less driving of cars, more restricted and healthful diet, and more careful segregation of illness

made England in wartime a safer place to live than in peace.

None of these statistics can be taken as in any way minimizing the horrors of warfare, and they are to a certain degree misleading in that active young men in the prime of life are selectively sacrificed in war, while the people as a nation show the mark of Mars for years. But the statement that civilization is likely to be destroyed by modern warfare is a shallow exaggeration. Even though nine-tenths of the human race were destroyed, if one out of each ten thousand who remained were a scientist with memory of the few facts that have been discussed in this book—the bases of communication, transportation, all of the things which aid in the dissemination of modern knowledge—that would be sufficient to re-establish civilization on this earth. Nothing brings back prosperity more quickly after a war than the application of scientific methods to reviving industry.

The destruction of civilization is not easy. Civilization contains innate self-stabilizing influences. Society has certain problems to solve and definite lessons to learn. The function of science is to speed up this learning process. If modern wars seem more terrible, it is because we are learning our lessons faster and overcoming more rapidly those obstacles to human progress which must be met in any case.

It is sometimes said that one cannot change human nature and that if science waxes uncontrolled, wars will endure until the end of time, becoming progressively more horrible as science provides more effective weapons. There is considerable likelihood, however, that science will itself be the cause of the removal of war in spite of human nature, for it is generally agreed among thinking people that war has its roots in lack of economic welfare. The recent war, stated to be between the "haves" and the "have-nots," is an instance of this, and certainly ambitious dictators would find little fuel

to feed their programs in a well-fed, well-satisfied citizenry.

We have already seen how science gradually raises the level of economic welfare, and how even at the depths of the worst economic depression the average man is far better off materially than his predecessor was at the height of the greatest booms of three centuries ago. We are prone to ignore the 95 per cent of blessings that science bestows, and to enlarge upon the 5 per cent of discomforts that acceptance of these blessings entails. The world needs, not less science, but more, to diminish that 5 per cent of discomfort. Science is nothing but learning, and it is a little learning that is a dangerous thing, not a lot. Science is knowledge, and knowledge is power—power over nature and over environment, power over adversity.

In what are sometimes called "the good old days," war, famine, and pestilence were considered inevitable. If half a man's family was wiped out in a week by diphtheria, that was the will of God. Now man has made use of his God-given opportunities to control famines which arise from natural causes. Through science the Black Plague, cholera, yellow fever, and a dozen other pestilences have been wiped out, and the rest are on the way. The twentieth century may well see war, this further "pestilence," eliminated, as through the natural sciences man gradually raises the level of availability of the things he needs for health, security, comfort, education, and enlightenment, by creating more and more order in nature.

We hear much about the "good old days," but the world is growing older every day, not younger. Opportunity knocks on every hand for him who has ears to hear, and there is ample evidence that the best "old days" lie ahead.

Suggested Books for Further Reading

New World Picture, by George W. Gray (Little, Brown, 1936). An authentic, well-written discussion of the present concept of the physical structure of the world and the universe, in terms of recent discoveries in physics and astronomy.

The Renaissance of Physics, by Karl K. Darrow (Macmillan, 1936). Gives in simplified form the technical details of much of modern physical discovery.

Introduction to Contemporary Physics, by Karl K. Darrow (Van Nostrand, 1926). A somewhat more technical description of the discoveries of modern physics.

From Galileo to Cosmic Rays, by Harvey Brace Lemon (University of Chicago Press, 1934). A textbook of elementary physics, written in form considerably different from the usual dry-as-dust treatment.

The New World of Physical Discovery, by Floyd L. Darrow (Bobbs-Merrill, 1930). A popular account of scientific discoveries as they contribute to daily life.

From Beacon Fire to Radio, by Walter Kellogg Towers (Harper, 1924). A history of the development of communication.

Signals and Speech in Electrical Communication, by John Mills (Harcourt, Brace, 1934). An interesting account of telephony and telegraphy, by a telephone engineer who is widely known for his writings.

A Fugue in Cycles and Bels, by John Mills (Van Nostrand, 1935). An authoritative discussion of how sound waves are handled.

Radio Round the World, by A. W. Haslett (Macmillan, 1934).

Presents in readable form the growth and recent developments of radio.

The Nature of the Physical World, by Sir Arthur S. Eddington (Macmillan, 1928). Contains much about atomic structure and the discoveries of modern physics in form which is readable by the intelligent layman.

Science for the Citizen, by Lancelot Hogben (Knopf, 1938). Almost a textbook of modern science, thorough and authoritative though incomplete. Though rather heavy going for steady reading, this book serves excellently as a reference book.

The Next Hundred Years, by C. C. Furnas (Reynal and Hitchcock, 1936). A very readable account of "the unfinished business of science." The enthusiasm of the author more than compensates for occasional errors of fact and judgment. The field of physics is probably least well covered.

Discovery, or, The Spirit and Service of Science, by Sir Richard Gregory (Macmillan, 1931). A philosophical book which tells, in writing of great beauty, how science in all its branches has contributed to society.

The Advancing Front of Science, by George W. Gray (Whittlesey House, 1937). A group of loosely connected though well written essays on recent discoveries in astronomy, physics, chemistry, and biology.

Atoms, Men, and Stars, by Rogers D. Rusk (Knopf, 1937). Contains much information about discoveries in modern physics, mingled with philosophical wonderings about what it is all good for.

The New Background of Science, by Sir James Jeans (Macmillan, 1934). A discussion in popular terms of some of the theoretical developments of modern physics, particularly relativity, quantum mechanics, and the basis of atomic structure.

Creative Chemistry, by Edwin E. Slosson (Century, 1921). Did for chemistry what the present book attempts for physics—to present concretely the contributions of the science to every-day living.

Photography, by C. E. Kenneth Mees (Macmillan, 1937). A read-

able and authoritative account of the development and present status of picture-taking.

Discoveries and Inventions of the Twentieth Century, by Edward Cressy (Dutton, 1930). A book which embryo inventors will find interesting.

The Drama of Weather, by Sir William Napier Shaw (Macmillan, 1933), *Rain Making and Other Weather Vagaries*, by W. J. Humphreys (Williams and Wilkins, 1926), *Physics of the Air*, by W. J. Humphreys (McGraw-Hill, 1929). Three good books on weather and weather predicting.

Tools of Tomorrow, by Jonathan Leonard (Viking, 1935). An interesting discussion of how science leads to engineering, and discovery to invention.

Explaining the Atom, by Selig Hecht (Viking, 1947). One of the best of the popular books explaining nuclear structure and the release of nuclear energy.

The Scientists Speak, edited by Warren Weaver (Boni & Gaer, 1947). A series of 81 brief excursions into science by prominent American scientists, originally presented as radio broadcasts.

Science Marches On, by Walter Shepherd (Harcourt, Brace, 1939). A popular discussion of present-day scientific progress.

Modern Science, by Hyman Levy (Knopf, 1939). A philosophical exposition for the layman.

New Worlds in Science, edited by Harold Ward (McBride, 1941). An anthology of carefully selected bits of popular science.

Science Remakes Our World, by James Stokley (Ives Washburn, 1942). Essays in Popular science.

Meet the Atoms; a Popular Guide to Modern Physics, by Otto R. Frisch (Wyn, 1947).

Scientists Against Time, by James Phinney Baxter III (Little, Brown, 1946). A description of the application of science to warfare in America during World War II.

Most of the scientific periodicals are too technical to interest the layman, but the following periodicals are recommended as

giving up-to-date semi-popular discussions of developments in applied physics:

The Bell Laboratories Record, New York, N. Y.
The General Electric Review, Schenectady, N. Y.
The Technology Review, Cambridge, Mass.

In Explanation and Acknowledgment

THE WRITING of this book was undertaken at the instance of the American Institute of Physics, central organization of the various societies of American physicists, to the officers of which it is a pleasure to express gratitude for stimulating co-operation. Dr. Henry A. Barton, Director, aided in many ways in the collection of material, and with Dr. Karl T. Compton, Chairman of the Governing Board of the Institute when the book was undertaken, contributed to its preparation with encouragement, criticism, and amiable patience.

Various chapters of the book appeared in modified form in *The Atlantic Monthly*, *Harper's Magazine*, *The Reader's Digest*, *The Scientific American*, and *The Technology Review*. Grateful acknowledgment is made to the editors of these journals for permission to reprint and adapt.

To the directors of and workers in various research laboratories the author is indebted for extension of the hospitality of their laboratories and for placing unpublished material at his disposal. For such courtesies it is a pleasure to thank Dr. Oliver M. Buckley, Dr. M. J. Kelly, Dr. Harvey Fletcher, and Mr. John Mills of the Bell Telephone Laboratories; Dr. V. K. Zworykin and Mr. E. W. Kellogg of the R. C. A.-Victor Laboratories; Dr. William Coolidge and Mr. L. A. Hawkins of the General Electric Laboratories in Schenectady; Dr. C. E. K. Mees and Dr. L. A. Jones of the Eastman Kodak Co.; Dr. Paul D. Foote of the Gulf Research Laboratories; and Dr. E. C. Sullivan of the Corning Glass Works.

To many other friends and colleagues acknowledgment is due for furnishing information and for criticizing sections dealing with

their respective fields of research. Outstanding among these are Dr. W. B. Rayton of the Bausch and Lomb Optical Co., Dr. Martin Grabau of the Polaroid Corporation, Dr. John M. Arthur of the Boyce Thompson Institute for Plant Research, Dr. Richard Dresser of the Huntington Memorial Hospital, and Professors J. C. Hunsaker, Robley D. Evans, Robert J. Van de Graaff, Stark Draper, Edward Schwartz, James Holt, and Hurd C. Willett of the Massachusetts Institute of Technology.

To Mr. John J. Rowlands, Professor Howard Bartlett, Mr. George W. Gray, Dr. E. E. Free, and Mr. J. Rhyne Killian, Jr., the author is deeply indebted for general advice and criticism during the early part of this writing. Professor Arthur C. Hardy has kindly aided in the final perusal of the proofs for errors of fact or form.

Finally, it is a pleasant duty to acknowledge the able co-operation of Mr. Thayer Hobson, Mr. George Libaire, and their colleagues of William Morrow and Co., who have contributed much in addition to the routine editing and publication of the book.

For those who may wish to read further regarding the ways of the physicist and his colleagues in related sciences, a brief list of suggested books is appended.

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